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GENERAL SYSTEMS PRINCIPLES: A FRAMEWORK FOR ORGANIZING, COMMUNICATING, AND INTERPRETING PROPERTIES OF THE NATURAL-URBAN CONTINUUM

Final Manuscript
to
The U. S. National Park Service
Office of the Chief Scientist
Washington, D.C.

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INTRODUCTION

The complexity of the natural and urban world of the 1970's has motivated a great deal of research directed toward an understanding of the interdependencies and commonalities between natural and urban systems. Titles of papers and books on the subject generally contain two or more of the words "energy, economics, ecology, and sociology." This body of literature apparently represents an attempt to understand the linkages among various disciplines and an attempt to provide some sort of holistic framework through which the current complexity can be organized, communicated, and interpreted. It recognizes that the real world does not function according to discrete discipline boundaries artificially imposed by the specialists in each discipline.

This paper represents a contribution to that body of literature. The framework offered here is a set of systems principles.* The approach is empirical; that is, the principles are attempts to explain observed phenomena and relationships. They hold for natural and urban systems and have a common origin in thermodynamics.**

The paper is divided into three parts. The first part introduces some terminology that is equally useful for discussions of natural and urban systems. The second part presents five systems principles along with examples for natural and urban systems. A final section identifies some of the implications of the set of principles for the natural-urban continuum and for the U. S. National Park Service. We take the view (as elucidated by Sudia, 3) that people are natural and that, therefore, technology and cities are natural. Rather than the conventional natural-urban terminology, we use the terms nonhuman-human throughout the remainder of this paper.

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* We wish to acknowledge the fact that much of what has stimulated our thinking on these principles and represents the kernel from which the concepts presented here were developed comes from the writings of H. T. Odum (1).

** Precise thermodynamic interpretations are excluded from this paper (see references 1 and 2).

THE NONHUMAN-HUMAN CONTINUUM: SOME SYSTEMS TERMINOLOGY

The discussions and examples of nonhuman and human systems included here focus on relationships among system inputs, storages, certain kinds of feedback and maintenance costs, and system outputs. Fig. 1a illustrates this basic input-storage-output module. Diagrams which incorporate this module in the form of examples of principles in nonhuman and human systems are included throughout this paper. Some commodity enters the system (source symbol in Fig. 1a, ○), is transformed into some other commodity (transformation symbol in Fig. 1a, ⟩⟩), and is stored in its transformed form (storage symbol in Fig. 1a, ◯). Some of what is stored must be "used up" in maintenance (maintenance cost pathway on Fig. 1a) and some must be invested in acquiring the inputs (feedback cost pathway on Fig. 1a). The additional input obtained is labeled feedback effect. Finally, after "paying" for maintenance and reinvesting in feedback, the system may have a net output. Output can be conceptualized as growth in the size of the storage or as an export "downstream" to some user of what was stored. This source-storage-output module is shown for a plant community (Fig. 1b) where sunlight is stored as biomass and for an industry where coal is stored in an extracted form (Fig. 1c).

The single source-storage module is the basis for a chain of modules where the output from one storage becomes the input for the next storage in the chain. A food chain is shown in Fig. 2a and an industrial chain in Fig. 2b. In the case of the food chain, sun energy

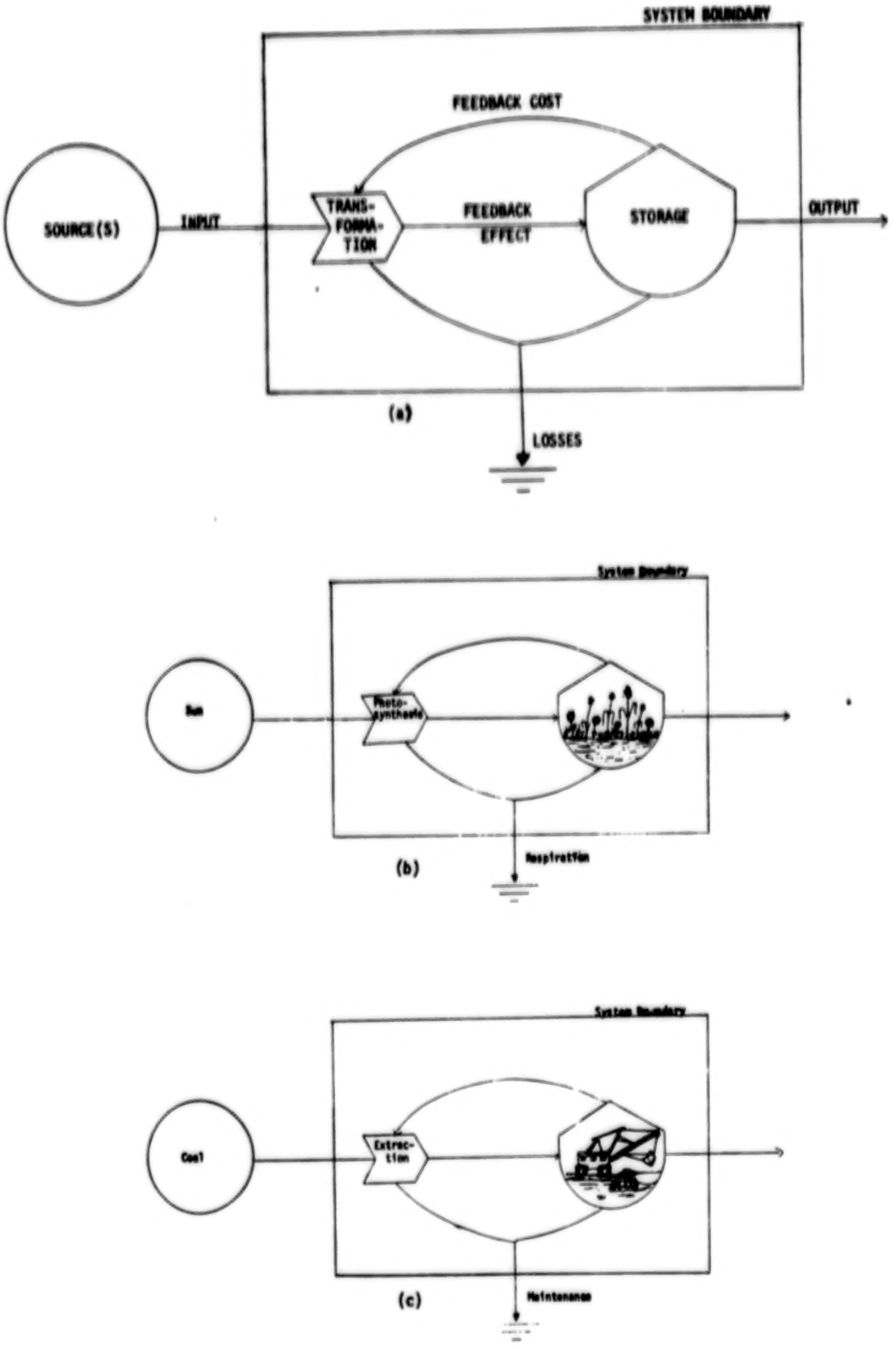

Fig. 1. Source-storage-output module and relationships among energy flows; the general case (a), a nonhuman system (b), and a human system (c). In the general case, energy from an external source is transformed and stored by the system, some stored energy is used (feedback cost) to "pump" in the source (feedback effect); any excess leaves the system as output. In the nonhuman system, sunlight is transformed via photosynthesis and stored as biomass; output is net primary production. In the human system, coal is extracted, stored and exported to industry.

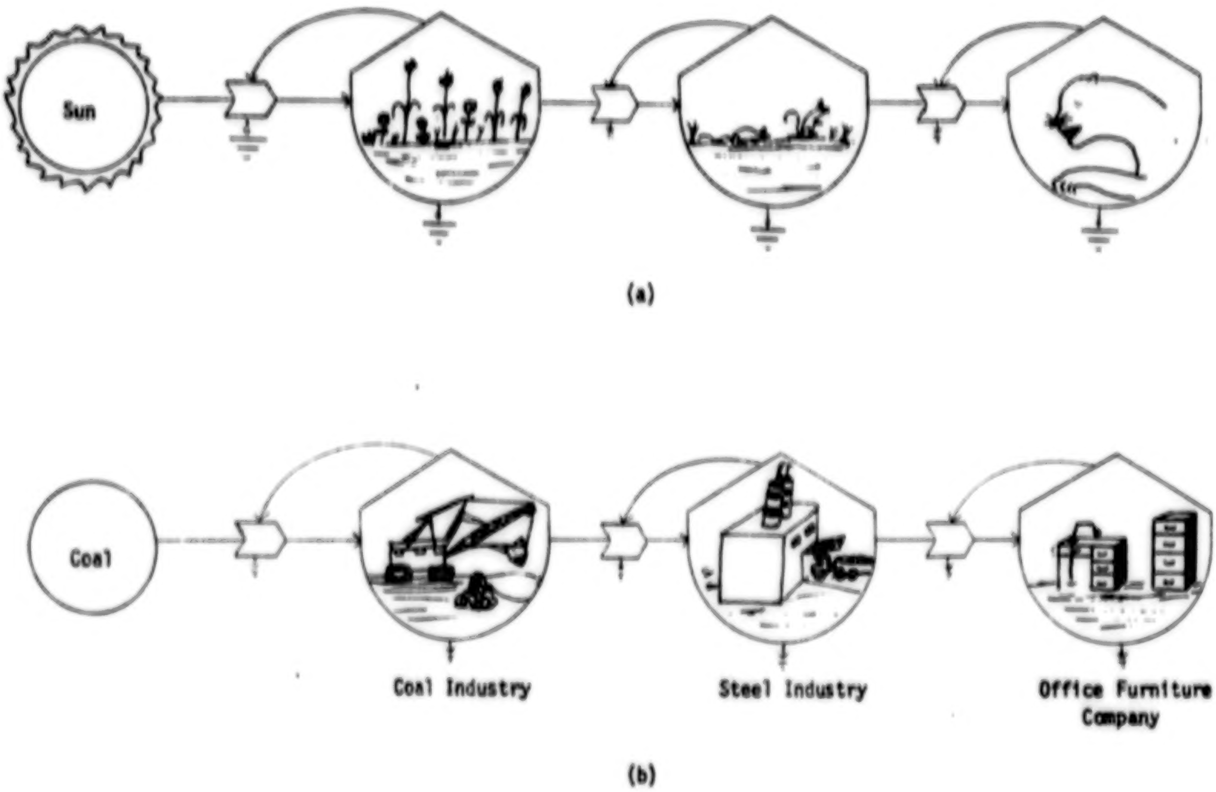

Fig. 2. Series of energy transformations in which energy is upgraded and stored; a nonhuman system (a) and a human system (b). Sunlight is stored as plants, herbivores, and finally as a carnivore (a); coal is stored as steel and office furniture (b).

is the basic input, the first transformation mechanism is photosynthesis and the initial storage is plant biomass. Net primary production is the output which is passed downstream, transformed via ingestion and stored as mice. Net secondary productivity is again passed downstream, transformed via predation, and stored as a mountain lion. There is a maintenance cost associated with the plants, mice, and mountain lion. Part of what is photosynthesized and ingested must be "used up" in maintenance. Similarly, part must be "used" in acquiring the source, e.g. the mountain lion uses up part of one meal in "catching" its next meal.

The industrial chain (Fig. 2b) is exactly analogous. Coal is the source of input. It is extracted by the coal industry, transformed first to steel, then to office furniture. Each industry has capital structure which must be maintained and each must reinvest part of what it acquires in obtaining more (feedback pathways).

As Figs. 2a and 2b indicate, the sun and stored fossil fuels are the most fundamental inputs to the earth's human and nonhuman systems. In any kind of human or nonhuman system, the commodities it requires and uses can be traced back "upstream" through a chain (or web) to sun or fossil fuel energy. But for more convenient system boundaries, any storage can be viewed as a source of input to the downstream user. For example, plant biomass is the input source to the mouse; the mouse is the input source to the mountain lion. Similarly, in the industrial chain, steel (not coal) is the input source from the viewpoint of the office furniture company. Thus, a storage stores something that was input from upstream but is itself an input from the viewpoint of the downstream user.

It is universally understood that the sun and fossil fuels are sources of energy; but, in this paper, storages are also viewed as sources of energy to some downstream user.* Fresh water, biomass, capital structure, information, ores, rocks, and soils are both storages and sources of energy. Table 1 gives some examples of energy sources which are stored and storages which become energy sources. In the nonhuman system column, energy sources are shown to be transformed to something new and then stored. The new storage is then shown as an energy source available for further transformation. For example,

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* The concept of storages being energy sources is based in thermodynamics; a storage is a source of energy when it has a measurable amount of "Gibbs free energy" relative to the ambient environment of the earth. That energy is available to do work. All storages discussed in this paper have free energy relative to the ambient environment and thus all are sources of energy.

Table 1: Energy Source and Storage Relationships in Nonhuman and Human Systems

Non-Human Systems			Human Systems	
Energy Source	Transformation Mechanism	Storage	Energy Source	Storage
Sun	Evaporation of Ocean Water	Fresh Water	Fresh Water	Reservoirs
Fresh Water	Hydrologic Cycle-erosion	Sediment	Sediment	Earth Filling
Sediment	Compaction	Minerals	Minerals	Jewelry, gems
Minerals	Differential concentration	Ores	Ores	Metal products
Minerals	Heat, Pressure	Rocks	Rocks	Buildings, roads
Rocks	Uplift Forces	Mountains	Mountains	Recreation, Hydroelectric Dams
Rocks	Erosion	Soils	Soil	Agricultural Products
Soils	Nutrient Uptake	Plants	Plants	Vegetables, Fruit
Plants	Ingestion	Herbivores	Herbivores	Meat
Herbivores	Predation	Carnivores	Carnivores	Zoos, Recreation
Sun	Photosynthesis, Pressure	Fossil Fuels	Fossil Fuels	Materials, Equipment, Capital Structure

sun energy transforms saline, ocean water into fresh water through evaporation; fresh water via the hydrologic cycle erodes and carries sediment to the ocean; sediments are the energy source for minerals; minerals for ores and rocks and so on through the nonhuman system column of Table 1. The human systems also store and utilize the energy sources created by the nonhuman systems. Examples of those storages are also shown in Table 1. Fresh water is stored in reservoirs, ores are transformed into metal products, and rocks into road construction material. Most importantly, fossil fuel is transformed into materials, equipment, and capital structure.

In short, what is a storage to one system may be a source to another. Conceptualizing source-storage relationships is done for convenience and depends on the system one wishes to examine. Choosing a boundary which places storages and transformations inside the boundary and sources outside the boundary has two implications. (1) It implies that the storages and transformations inside the boundary can change as a result of variations in the source. But, (2) the source is shown external to the boundary because, for the purposes of analysis, it cannot change as a result of variations in storages and transformations inside the system boundary.

The five systems principles included in this paper focus on these source-storage relationships. The relationships represent an organizational framework. As Fig. 1 indicates, any system includes a storage, maintenance of its storage, and a feedback mechanism with which to acquire inputs. Additionally, all kinds of inputs can be viewed as energy sources; what is a storage within one system may be an energy source to another.

FIVE SYSTEMS PRINCIPLES: APPLICATIONS TO THE NONHUMAN-HUMAN CONTINUUM

Each principle describes some system characteristic or response that has been observed. The characteristic or response is functionally the same in nonhuman and human systems. In addition, each principle is mutually dependent on one or more of the others. Together they represent a complex of ideas rationally dependent on each other. Thus, the sequence in which they are discussed is arbitrary and any sequence poses organizational problems since the dependency of one principle on another can only emerge as the sequence proceeds.

The sequence chosen here reflects a kind of pragmatic hierarchy. It begins (principle I) with a discussion of why systems transform and store certain inputs; that is, with what the advantages of such transformations are. Systems also produce outputs which they reinvest. The second principle examines how that reinvestment takes place in a growth situation. But growth is not always possible due to supply irregularities and limitations. System responses and adaptations to supply irregularities are taken up in the third principle and to supply limitations in the fourth principle. Finally, the issue of what constitutes a "best" or successful response to a growth situation or to supply irregularities and limitations is addressed by the fifth principle. For each principle, we state an observation as a question. The systems principle is then given as one answer to the question. The principle is then discussed and examples in nonhuman and human systems identified.*

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* There are undoubtedly hundreds of examples of each principle, see, for example, literature reviews and analogs by Hessler (4). We identify only a few relying on general literature (4,5) which considers nonhuman and human systems in the context of holistic principles.

Transform and Store

Question: Why do systems transform and store inputs?

Principle: Inputs are transformed and stored in order to increase the speed with which more of the input can be obtained.

Discussion:

The basic source-storage module indicates that part of what is stored is fedback to the transformation mechanism through which the input is acquired. The transformation mechanism can be conceptualized as a pump; literal examples are given in Figs. 3a and 3b — a human operating a water pump (Fig. 3a) and a generator operating an oil pump (Fig. 3b). Flowing through the pump from outside the system is one of the system's sources of energy (water for the human and oil for the generator). But the 'pump handle" or the energy needed to operate the pump actually comes from the storage itself, it is the feedback cost. In Fig. 3a, the human must expend part of his/her stored energy to obtain the water. The water is one of the person's energy sources; the person is the storage and provides the energy to operate the pump; and the water is upgraded via the person's metabolic processes into human biomass. In Fig. 3b, stored fossil fuel in a generator operates the pump that pumps the oil out of a stripper well.

Four observations about this process of obtaining "energy" are important for the nonhuman and human systems considered here. First, the source is stored in some upgraded form, e.g. the human stores water in the form of human biomass. Second, the storage has a maintenance

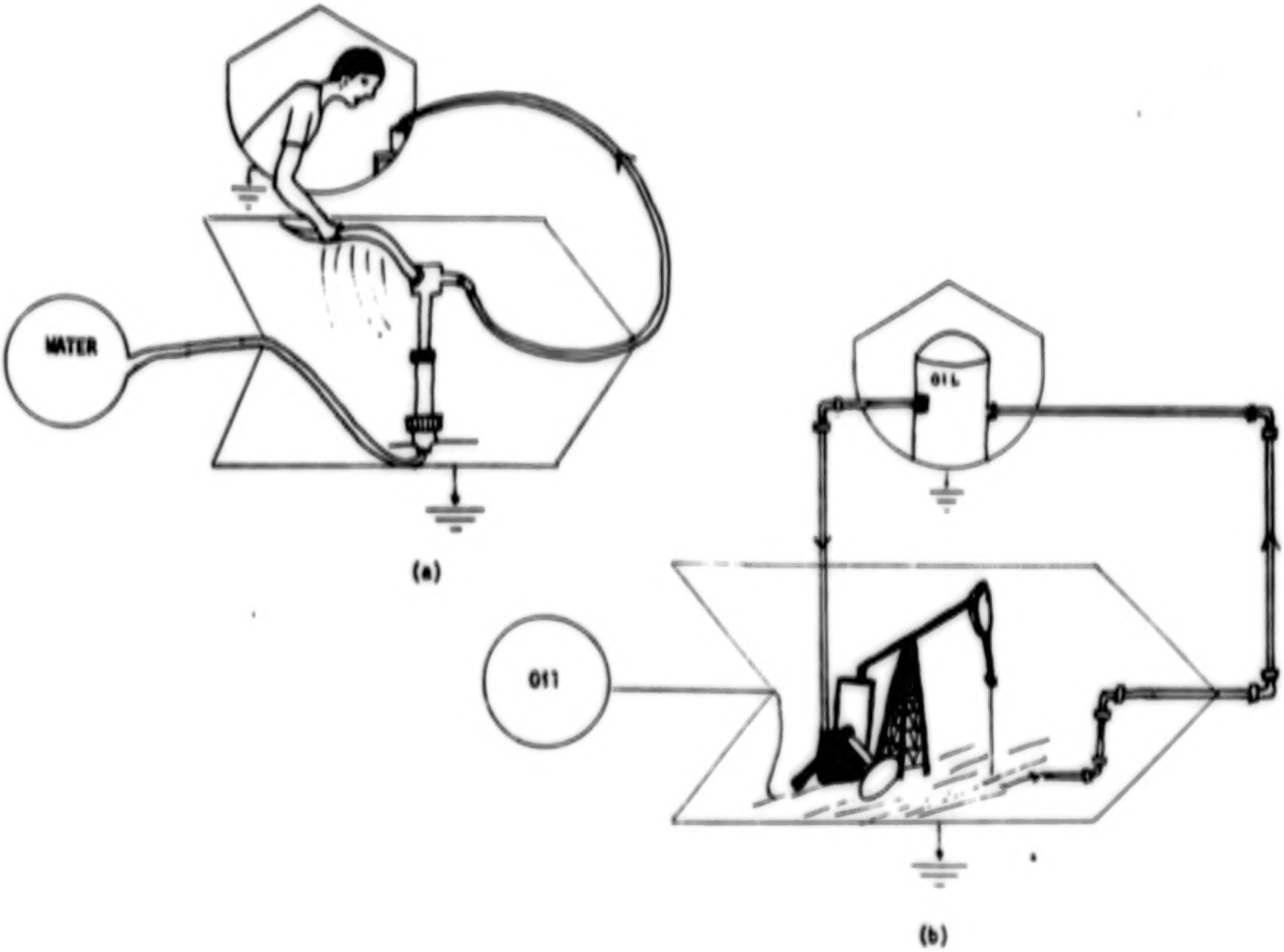

Fig. 3. The storage considered as an internal source of energy which "feedsback" to pump in more of the external source; the general case (a) and two literal examples — human energy pumping water out of well (b) and oil burned to pump oil out of a well (c). The human energy expended and oil burned represent the feedback cost of obtaining the external sources (water and oil).

cost associated with it. Part of the energy acquired must be "wasted" just to maintain the storage in working order (the human biomass or generator). Third, part of the energy acquired must be fed back to obtain more; as with maintenance, part of the energy acquired must be "wasted" to obtain more (that is, to operate the pump). Fourth, the amount of energy acquired must be greater than that "used up" to obtain it. In the water pump example, the human gets thirstier when he/she operates the pump (a feedback cost) but can obtain more water from the well than required just to quench that acquired thirst. Similarly, the generator can pump out more oil than just the quantity

Table 2: Energy Sources and Storages in Nonhuman Systems

Energy Source	Upgraded Source As A Storage
Sun	Biomass
Wind	Storms
Soil Nutrients	Plant Biomass
Plant Biomass	Animals
Sun	Information As Genes and Chemical Systems
Sun & Information	Diversity As Species, Niches, Adaptations, Interactions

used up by the generator. In systems terminology, this is called a feedback amplifier effect; it represents a way to accelerate the flow of energy into storage.

Thus, the overall function of a storage is to obtain more of its source of energy; in fact, to accelerate that flow. It accomplishes that function through some kind of feedback mechanism designed to do the "pumping." While the water and oil examples are literal examples of pumps, any storage represents a transformed and upgraded form of its source of energy; and, in all cases, part of what is stored is used via the feedback to accelerate the flow of more input to storage.

A. Nonhuman Systems

For nonhuman systems, Table 2 gives examples of energy sources and of storages which represent upgraded forms of these sources. The first example is that of biomass storage shown as upgraded and stored sunlight. The plant biomass must be maintained, but, more importantly,

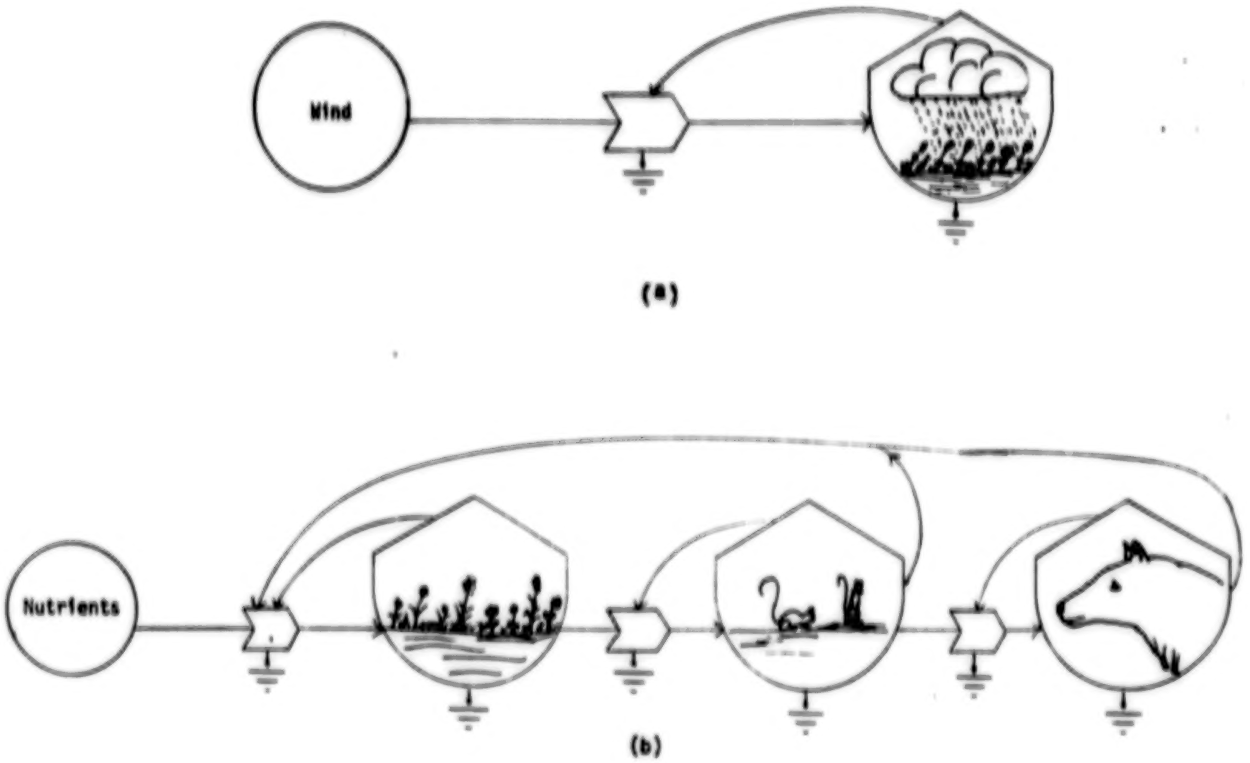

Fig. 4. The upgrading and storing of energy in nonhuman systems; wind energy is upgraded and stored as storms (a), and soil nutrients are upgraded and stored as biomass in a foodchain (b). Each storage contributes part of what is stored to "pump" in more.

part of the biomass is used to pump in more sunlight. For plants, these maintenance and feedback expenditures are measured as respiration. By virtue of the biomass storage, more photoreceptors are available to obtain sunlight and a root system is available to obtain nutrients and water. In a food chain, the herbivores that consume the biomass upgrade and store the plant biomass and so on through the remainder of the food chain. By virtue of each storage along the food chain, the amount of input obtained is accelerated.

Other examples given in Table 2 include storms as wind energy storage (Fig. 4a) and plants as soil nutrient energy storage (Fig. 4b). In each case, the storages (storms and plants) feed back and "pump" in more of their source (wind and nutrients, respectively). In the nutrient example, the animals in the chain also accelerate the flow

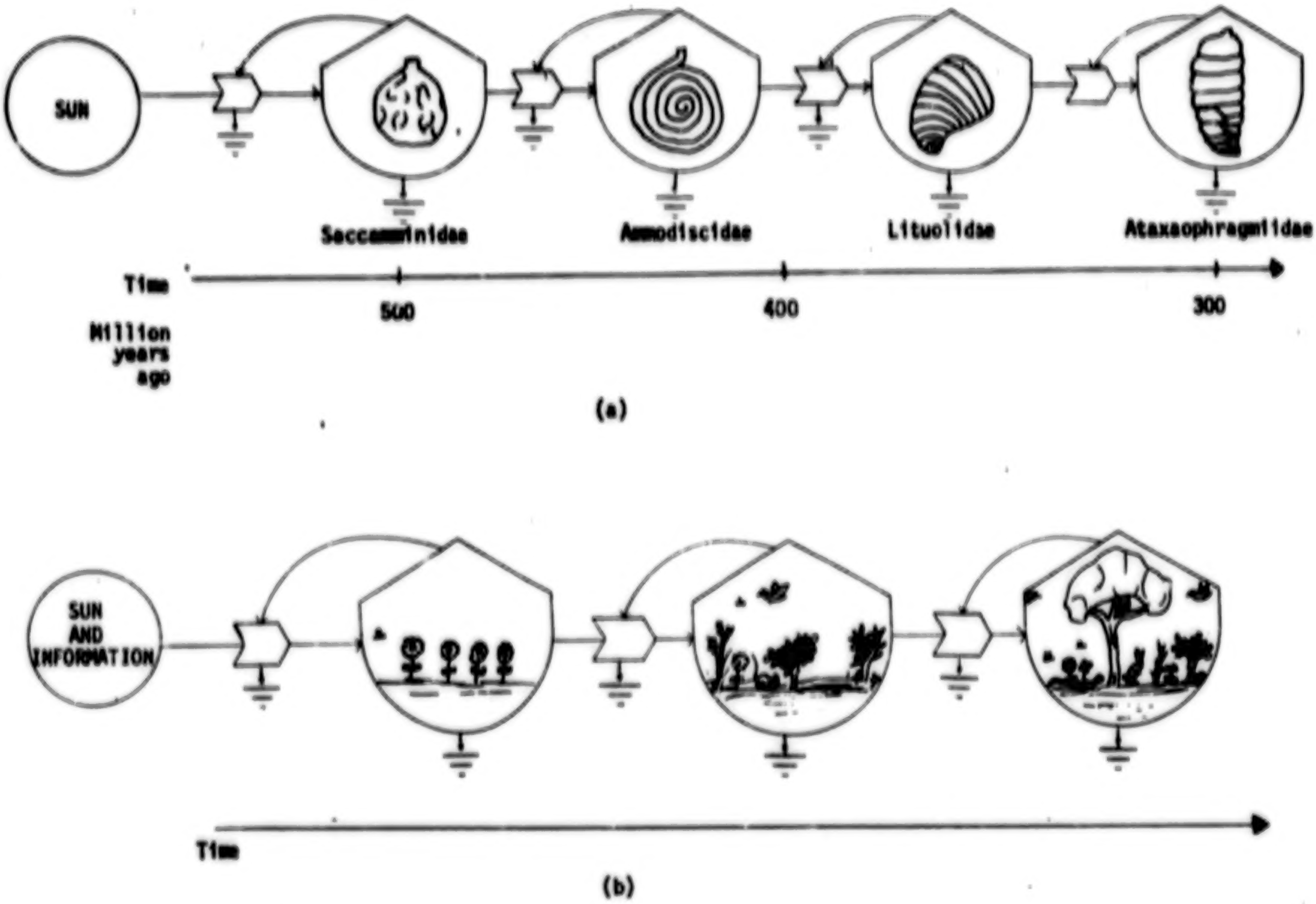

Fig. 5. Examples of upgrading and storing sunlight as information (a) and as diversity (b) in nonhuman systems. Information is stored in genes and used along with sunlight in the evolution of a foraminifera to create more information through time (a). Diversity is used along with sunlight and information to create more diversity through time (b).

of nutrients by contributing nutrients themselves; they feedback part of what they store to the beginning of the chain.

This source-storage-feedback relationship also seems to hold when the dimension of time is added and considered. As indicated in Table 2 and Fig. 5a, sun energy over time has "created" information stored in the genes and chemical systems that have evolved. The information "feeding back" over time apparently accelerates the process. At the ecosystem level, the combination of sun energy and this information over time "creates" diversity which is stored as species in assorted niches with assorted adaptations and interaction mechanisms (Fig. 5b). This stored diversity, again, acts overtime to accelerate

Table 3: Energy Sources and Storages in Human Systems

Basic Energy Source	Intermediate Storage as Upgraded Source	Final Storage
Sun	Food	Humans Physical Biomass
Fossil Fuel	Goods and Services	Material Biomass
Sun, Fossil Fuel	Information	Genes, culture, libraries, computers
Sun, Fossil Fuel, Information	Diversity	Cities and Nations

the "creation" of more diversity. Diversity is stored in a variety of abiotic and biotic components. Rainfall, temperature, relief, altitude, soil types comprise abiotic diversity. For the biotic components, diversity is measured as the number of species per number of individuals in recognition that species function as producers, herbivores, carnivores, omnivores, and decomposers with an additional diversity of interaction (parisitism, symbiosis, solitariness, and herding or swarming).

B. Human Systems

In twentieth century human systems, nearly all storages represent upgraded fossil fuel and sun energy. Table 3 lists sources of energy and storages which represent upgraded forms of those sources. For clarity, Table 3 shows storages in their intermediate and final forms.

The first example given in Table 3 is that of twentieth century humans in the U. S., shown as upgraded sun energy (as represented by the biomass of the physical body) and as upgraded fossil fuel (as

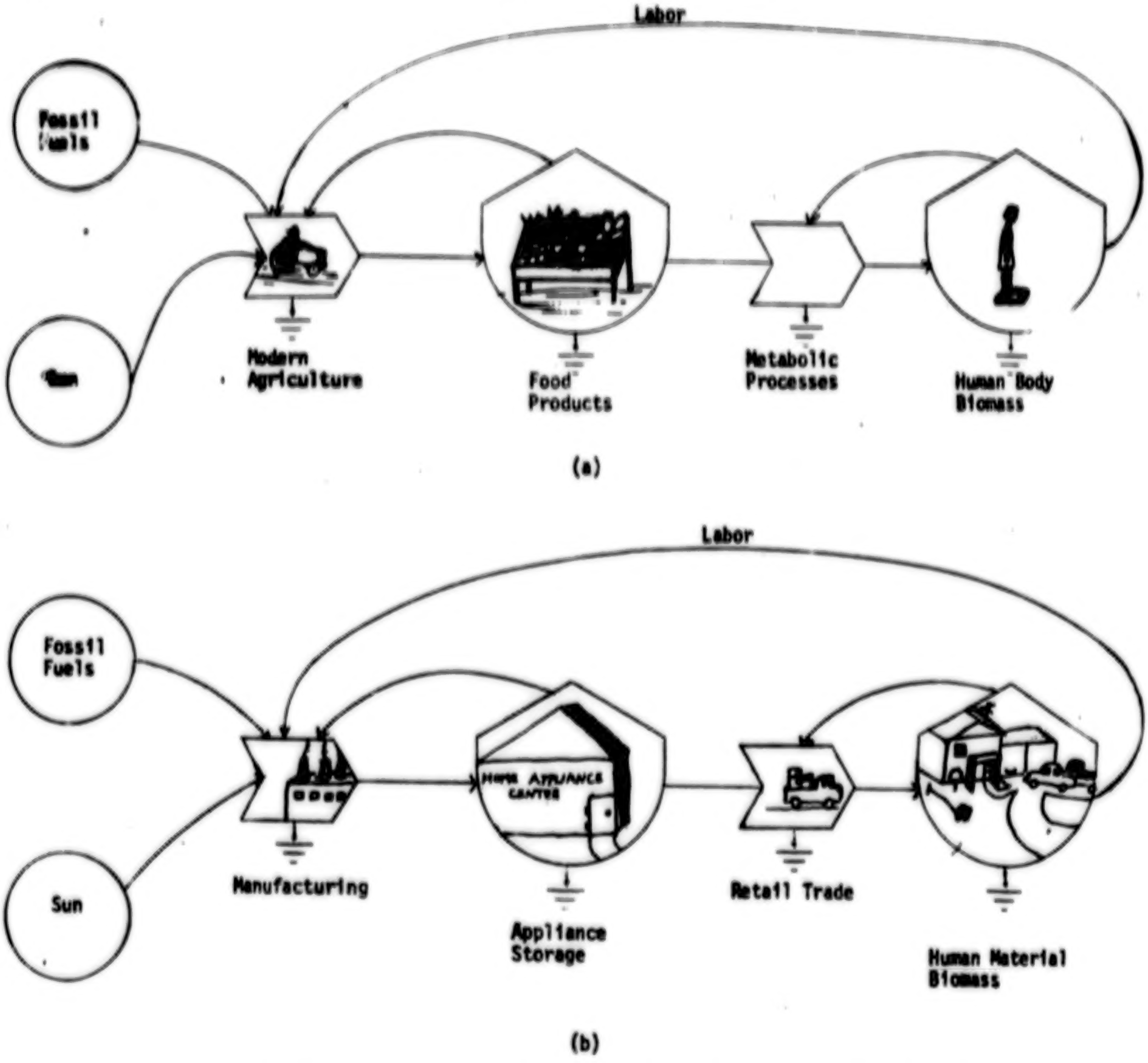

Fig. 6. The upgrading and storing of energy in human systems; storage as human body biomass via a food-chain (a) and as human material biomass via an industrial chain (b). Both chains use labor feedbacks to "pump" in the external energy sources of fossil fuel and sunlight.

represented by material possessions). Human "biomass" has been extended beyond that of the physical body to include material possessions. Without the material possessions, human systems are an extension of the food chain (discussed earlier) as hunters and gatherers. For example, we have recently witnessed the great difficulty in separating people from their automobiles; the automobile has become part of the biomass along with the house, furniture, and appliances.

The system supporting the body biomass is shown in Fig. 6a and that supporting the material "biomass" in Fig. 6b. The external sources of energy shown include the sun and fossil fuels. In agriculture (Fig. 6a), the sun is clearly required and utilized directly. In industry, its use is less direct but nevertheless is required. Manufacturing processes use natural resources as raw materials (water, rocks, and ores) and as waste sinks (water, air, and land). These are simply grouped in Fig. 6b and labeled sun energy. In this human system, the feedback that accelerates the flow of energy into the human storage (i.e. pumps it in) is labor. Thus, as with the nonhuman systems, both the human biomass and all material possessions must be maintained and part of what is stored must be used via the labor feedback to acquire more.* In short, as with a simple biotic food chain, the human storage is required to obtain its energy inputs and is itself an upgraded form of those inputs.

With time, sun and fossil fuel have been and are converted to information as stored in genes, culture, libraries, and computers (Table 3). As shown in Fig. 7a, the storage of information in a library enables procurement of more information. The library must be maintained and feeds its information to an educated population which then produces more information in an ever accelerating fashion.

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* Note that the dollar cost of maintaining "labor" is the Gross National Product. At the level of an individual, this dollar cost is thought to represent some measure of standard of living. Dollar costs or wages clearly represent maintenance of both physical and material "biomass." Thus the energy cost of maintaining labor is, philosophically, the same notion as the dollar cost; it is only the units that are different. An important unanswered question is the extent to which the energy costs of maintaining the GNP and the individual's standard of living can decrease while the dollar costs remain constant or increase.

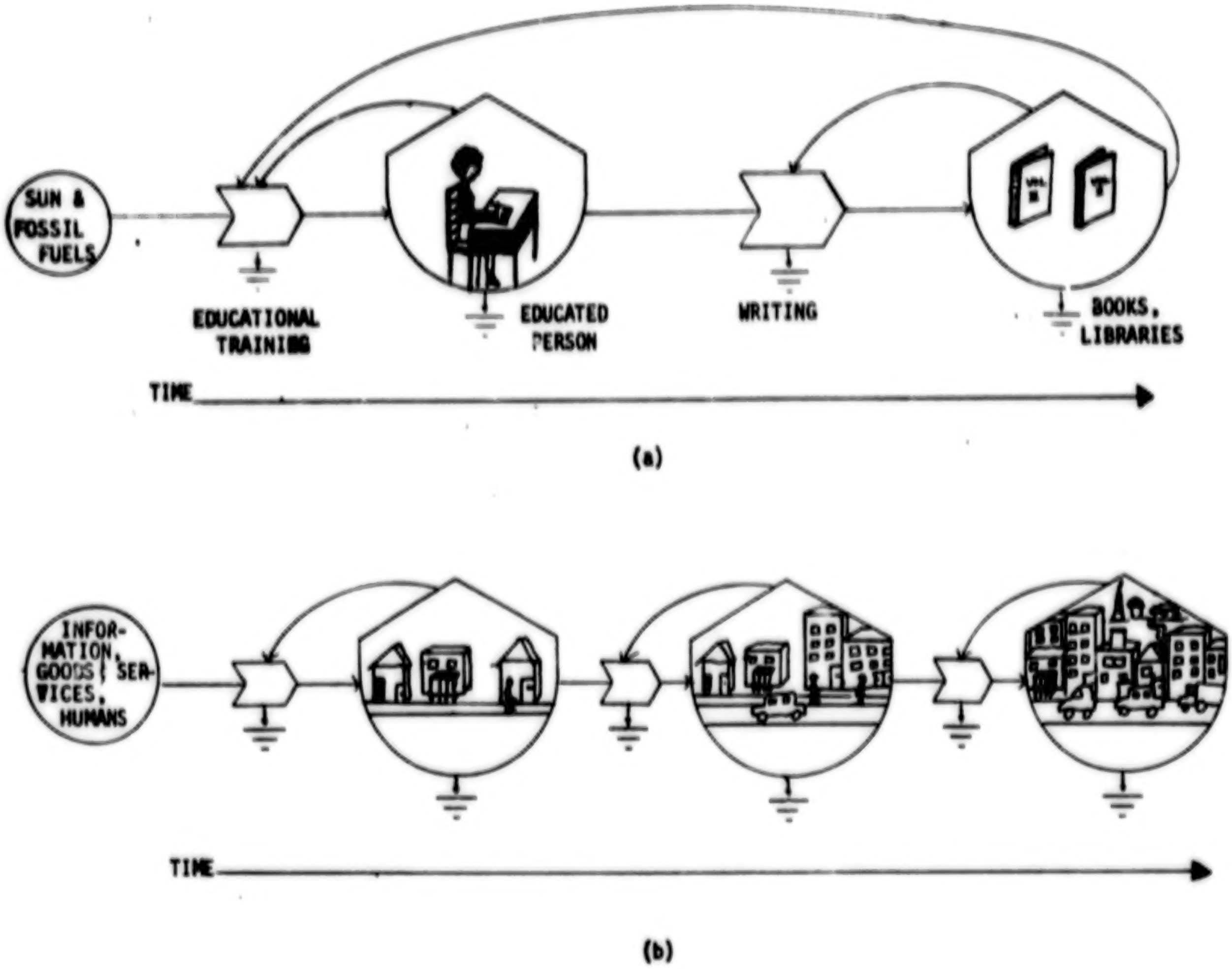

Fig. 7. Examples of upgrading and storing sunlight and fossil fuel as information (a) and as diversity (b) in human systems. Information is stored in books and used along with sunlight and fossil fuels (as required for educational training) to create more information through time (a). Diversity is used along with goods and services (made with sunlight and fossil fuels) to create more diversity in cities through time (b).

Finally, this information along with goods, services, and humans is upgraded and stored as the diversity within and among our cities (Table 3). As shown in Fig. 7b, the city must be maintained and uses some of its storage to acquire more of its needs. A diversity of industry, suburbs, business, ethnicity, culture, and taste act in combination to accelerate the flow of many kinds of energy inputs into the city; the city itself is an upgraded form of all of those inputs.

Fig. 8a represents a sort of summary of the current U. S. source-storage-feedback structure.* The U. S. is consuming about 74 quadrillion Btu's of fossil fuel per year. Two kinds of storages are "pumping" it in and through the economic systems: industrial capital structures (labeled Feedback F1 on Fig. 8) and cities (labeled Feedback F2 on Fig. 8). Fossil fuel is processed in industry's capital facilities to make goods and services and the goods and services maintain the city and its human population. Both the industrial capital structure and the city storages are required to obtain the fossil fuel and both contribute some of their stored energy in feedbacks 1 and 2 to obtain it.

For example, consider the requirement for capital structure and for a city at the level of one industry. The oil industry requires both an oil rig and a petroleum geologist to acquire oil. The oil rig is part of the capital structure storage and the geologist is part of the city storage. Figs. 8b and 8c represent each part of this total requirement. The oil rig finds oil, part of that oil is used to make another drilling rig which then finds more oil (Fig. 8b). Similarly, the petroleum geologist finds oil, part of that oil is used to "make" another petroleum geologist (educate him/her in a university) who then finds more oil (Fig. 8c). The oil rig chain shown is a disaggregation of the capital structure storage and the petroleum geologist chain is a disaggregation of the city storage.

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* Fig. 8 shows only the fossil fuel supported system; the solar energy support while present is excluded for clarity.

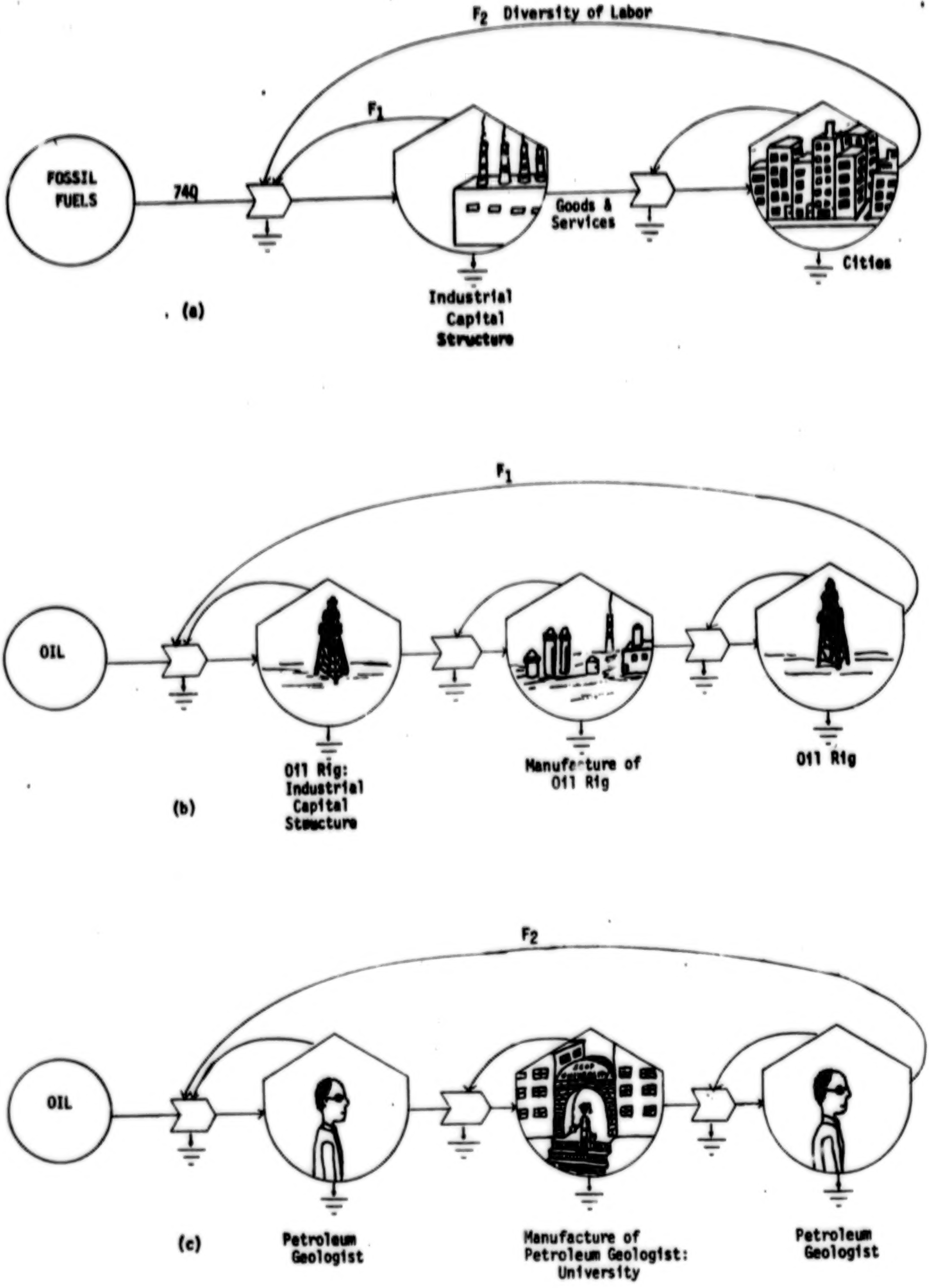


Fig. 8. Current U. S. source-storage-feedback structure. Two feedback types are required to "pump" in fossil fuel (a): industrial capital structures and labor. In more detail, industrial capital structure is represented by an oil rig (b) used to pump in oil; the oil, in turn, is used to make more oil rigs. Labor is represented by a petroleum geologist (c) used to pump in oil; again, the oil is used to "make" more petroleum geologists.

Summary

It is an observable fact that systems upgrade and store their input energy sources. The first principle indicates that they do so in order to accelerate the flow of that input. The acceleration is carried out via some feedback from the storage. Continuous production, storage, and feedback loops operate in both human and nonhuman systems. But, for most of the systems discussed, the feedback from storage is so efficient that it pumps in more energy than it needs for maintenance. The result is some net accumulation or net production of an output. The utilization of that net output is taken up in the next principle.

Reinvesting Output

Question: What is the response of a system to surplus output?

Principle: The system responds by reinvesting the output so that more of the sources can be obtained and internalized.

Discussion:

Surplus energy, or output, is produced when the energy used by the system for maintenance and feedback is less than the energy obtained. For the literal examples of a water and oil pump given earlier, the human can pump out more water than is required to quench his/her thirst and maintain cells. Similarly, the generator can pump out more oil than it requires for operation and maintenance. Empirical evidence suggests that this surplus or net output is reinvested through some feedback pathway. Apparently, that reinvestment takes three forms: it is used to increase the size of the pre-existing storage, to create a new mechanism to obtain the same source, or to obtain a new source(s). By coupling net output, the system grows and is transformed.

These reinvestment responses are observed on all systems levels from individuals to ecosystems. Examples will be discussed for nonhuman and human systems for the three reinvestment modes: increasing the storage size, developing a new mechanism to obtain the same source, and obtaining a new source.

A. Nonhuman Systems

The reinvestment of output in order to increase storage size is a means for the system to internalize more of the external source. On an individual level an obvious example of output being coupled through storage size increases is that of a seed developing into a mature tree. The storage is biomass and for the system it represents an internalizing of solar energy through photosynthesis. In the growth sequence storage size increases with root development, bole diameter and leaf canopy. Similarly, areal growth of a pioneer plant species represents the coupling of output through additional storage. The nucleus colony (using the sun, nutrients and water) is able as a species to internalize these sources by seeding. The lateral expansion of the community is growth as biomass storage. As with a pioneer plant species, a plant community reinvests net output such that storage size increases with concomitant areal expansion of the community or increased density (biomass per unit of area).

After some quantity of the source has been internalized as storage, net output is reinvested in a new and different mechanism for obtaining the source. In other words, a new type of "pump" is apparently established. Some of the existing storage must be used to operate the pump. As the pump draws in more of the source, a new storage may be created and increase in size as the pre-existing one is "drained." Creation of a new storage and draining the old one represents growth and transformation to a new form.

For example, at an individual level, at some point a beech tree (*Fagus grandifolia*) accumulates excess quantities of solar energy, nutrients and water. After that point, rather than increasing its individual size (height, or width) it establishes new mechanisms to obtain these sources. In this case, the new mechanisms are runners and "daughter" shoots. The mother tree must use some of her stored sources as a pump in the form of runners and offshoots. The offshoots are a new storage and represent a method to internalize more energy (sun, water and nutrients). The transformation is from an individual to a colony.

Similarly, bee colonies increase storage size and then establish a new "pumping" mechanism. Initially, sterile females are reared, and food collection and reproduction are done by the workers. When the storage, as individuals and honey, reaches a certain size a new queen is "made" by rearing one larva on a special diet. She, then, takes some of the workers and forms a new hive. The original hive becomes several, all collecting and processing food.

On a larger systems level, succession represents the transformation of one seral stage to another. The output of one stage is consumed in the recoupling process that develops the next. As illus-

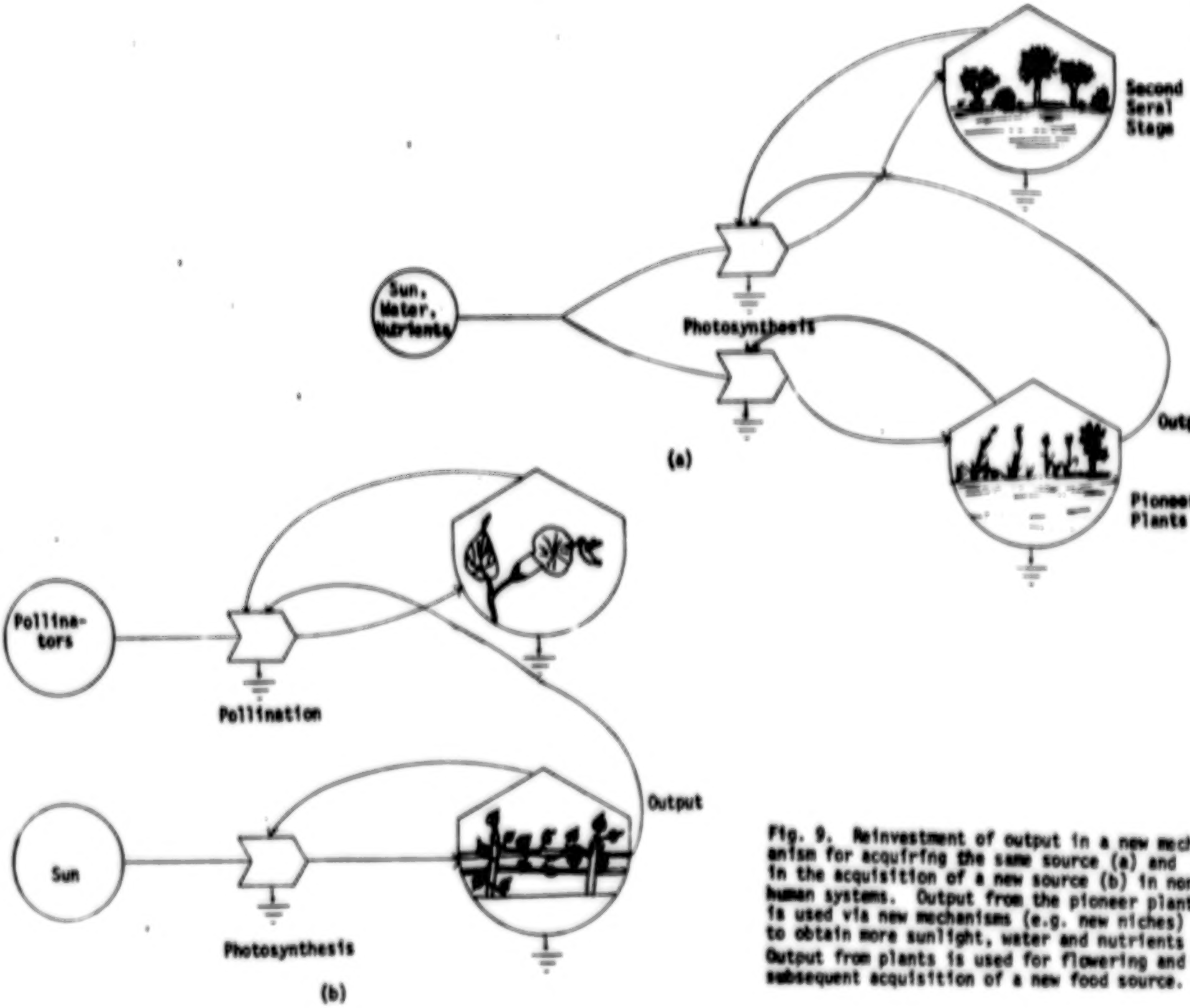


Fig. 9. Reinvestment of output in a new mechanism for acquiring the same source (a) and in the acquisition of a new source (b) in non-human systems. Output from the pioneer plants is used via new mechanisms (e.g. new niches) to obtain more sunlight, water and nutrients (a). Output from plants is used for flowering and the subsequent acquisition of a new food source.

trated in Fig. 9a the pioneer plant species (using solar, nutrient, and water energy sources) produce an output. The output is reinvested in the establishment of new plant species (second seral stage). For example, the nutrient output from the pioneer species and the additional niches those species create are used to support the next community.

The third alternative reinvestment strategy is to reinvest output in such a way that a new external source is acquired and internalized.

This process involves the establishment of a new pump and the use of some of the existing storage to operate the pump. As with the previous mode of output coupling, additional storages may be created and the character of the system changes.

An example at an individual level is a plant which uses solar energy, nutrients and water as energy sources to grow roots and leaves. The extra output from vegetative growth may be invested to produce flowers, rather than more leaves. The petals and nectar "made" with the surplus are used to draw in a new energy source (pollen). As illustrated in Fig. 9b, the new energy source is internalized as a storage of seeds and fruit. On an ecosystem level, net primary production (an output) is used to support herbivores and carnivores. If the output is dead wood it is reinvested in mushrooms and other decomposers. By generating organic matter, the consumers and decomposers, in turn, accelerate the supply and accessibility of nutrients to the plants. The ecosystem establishes a new mechanism for obtaining nutrients.

B. Human Systems

The same kind of responses to the production of an output that are observed in nonhuman systems occur in human systems also: reinvestment for storage size growth, for new mechanisms to acquire the same source and for acquisition of new sources.

An example at an individual level of reinvestment for storage size increase is that of human physical growth from an infant to an adult. Infants consume more food than required to maintain their small biomass. The excess is invested in growth as tissues, muscles, and fat. Similarly, human individuals reinvest material possessions to increase their storage of those possessions. Appreciation on one house is reinvested in another, bigger one. Individual cultural storage also increases in a lifetime. One manifestation of cultural storage is behavior which is often measured qualitatively by how "cultured" or "well adapted" an individual is. The process is one of internalizing social mores.

On a larger systems level, a town reinvests its output to acquire goods and services which are, in turn, used to build buildings and roads. Reinvestment continues and growth continues. It is an observable fact that, as a freeway develops through a city, restaurants, gasoline stations, and residential developments grow in a "strip" fashion along the freeways. The freeway has outputs which are coupled to more growth so that the freeway is no longer just a road but a strip of development. Other examples include reinvestment of food in population growth and reinvestment of information in an educated population, in libraries, and computers.

As in nonhuman systems, increased storage size finally gives way to new mechanisms and new kinds of storages utilizing the same source. At an individual level, the information stored via a college education is invested in a job which further increases the individuals information storage. Whereas the college was "pumping" in information, now the occupation is doing the pumping; the cycle continues throughout a lifetime. The student is transformed into a professional.

Similarly, a group of people with no governing body may reinvest surplus output acquired from goods and services by forming some type of government (Town Clerk or Town Elders). As a community becomes a

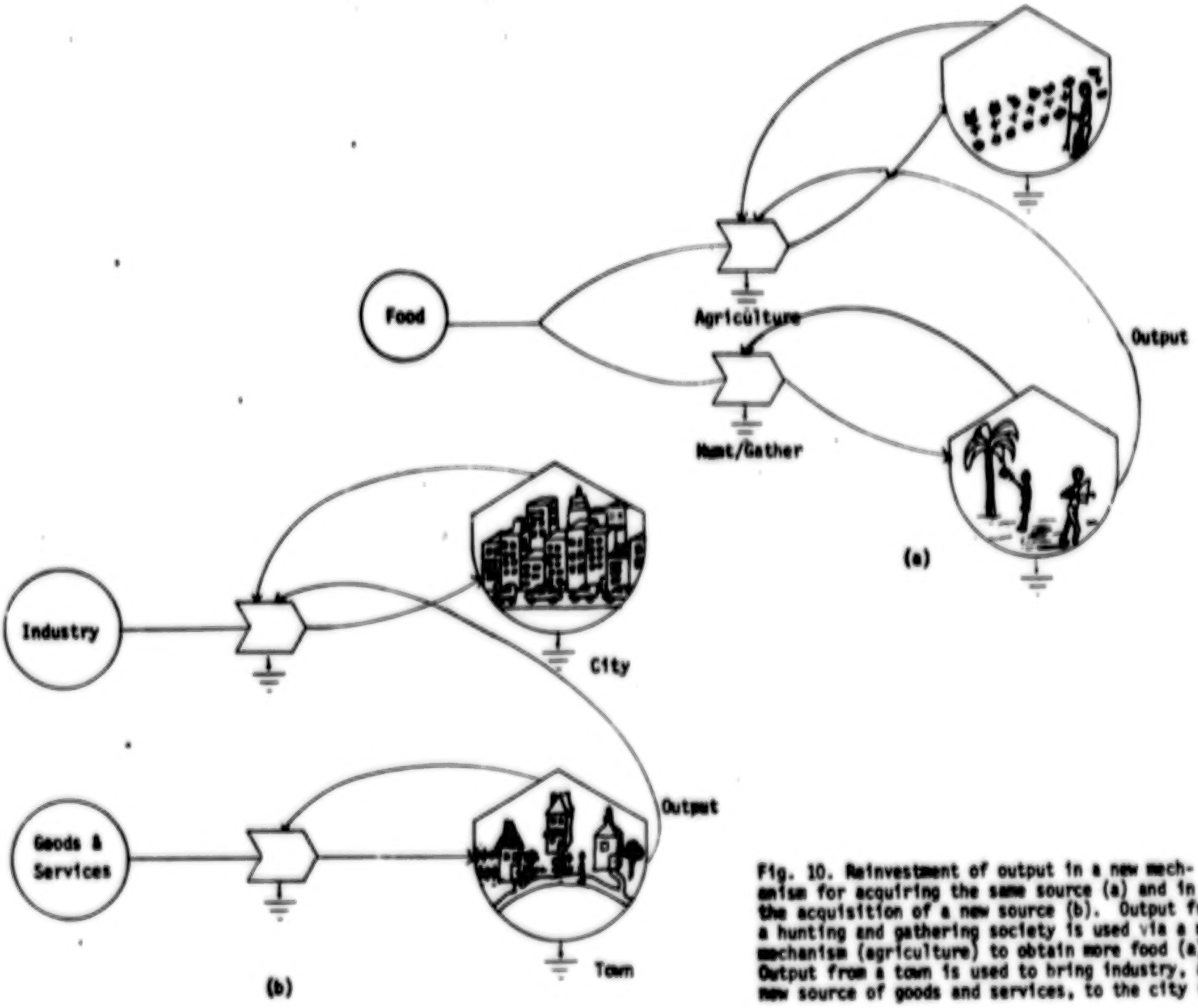


Fig. 10. Reinvestment of output in a new mechanism for acquiring the same source (a) and in the acquisition of a new source (b). Output from a hunting and gathering society is used via a new mechanism (agriculture) to obtain more food (a). Output from a town is used to bring industry, a new source of goods and services, to the city (b).

town, the goods and services are now pumped into the town in greater amounts because of the bureaucratic organization. In the past, the output from hunter and gatherer peoples was reinvested in the development of agriculture as a mechanism for obtaining food. As illustrated in Fig. 10a, the transition from a hunting/gathering society to a farming society occurs as the initial storage is transformed via a new energy pump (agriculture).

Eventually, new sources must be acquired and output is reinvested in mechanisms which internalize those new sources. As shown in Fig. 10b, a town reinvests to attract industry and is transformed to a city. Similarly, the output from solar based agriculture has been reinvested in the acquisition of fossil fuel based sources of equipment, fertilizers, and pesticides. The solar based agricultural system has been transformed to an agrobusiness system, which has been shown to be highly dependent on fossil fuels (6).

Summary

Empirical evidence suggests that systems reinvest output in a manner that results in the acquisition and internalization of more energy. That reinvestment of output apparently takes at least three forms. It may be used to internalize more of the same source by increasing storage size, to establish new mechanisms to obtain the same source, or to establish new mechanisms to obtain a new source. In all cases, more energy is put to work in the system and growth results. But, reinvestment for growth can only occur when external sources are untapped and reliable. The response of a system to unreliable sources is discussed in the next systems principle and to limited sources in the following.

Unreliable Sources

Question: What is the response of a system to an irregular or unreliable source?

Principle: The system responds to irregularities by temporarily increasing the storage size or reducing the quantity required.

Discussion:

An unreliable source is defined here as one that is periodically rather than permanently limited. Unreliable implies that the source is "off" temporarily and that the system has some knowledge that the same source will be available again in the future. This knowledge is acquired through evolution and stored in genes in nonhuman systems and acquired through conscious thought based on history and models of the world in human systems.

Empirical evidence suggests that there are two common responses of systems to temporary supply shortages. One is to internalize more of the external source (by increasing the storage size) when it is available and use that storage when the external source is unavailable. The second is to adjust so as to not use the source (by dormancy or migration) when it is unavailable. Examples of responses to various kinds of unreliable sources are given in Table 4, and some are discussed below.

A. Nonhuman Systems

Storage of unreliable sources of water, food, and sunlight will be discussed first, followed by adaptations to not use the source when unavailable. Both of these responses "smooth out" the "on-off" effect of unreliability.

(1) Response: Increase the storage size.

Because the desert is characterized by dry and wet seasons, many desert plants collect and store water when available (wet season) and use the storage as an external source when it is unavailable. The Saguaro cactus (Cereus giganteus) for example can use its storage of water through several years of drought

Table 4: Examples of Systems' Responses to Unreliable Sources

Response	Unreliable Source	Examples	
		Nonhuman Systems	Human Systems
Increase Storage Size	Food/Nutrients	Plant seeds Squirrels-nuts for winter Bees-honey for winter Ants-plant juices for dry season Wasps-paralized insects for larva Crowns, enlarged root tubers-plants for winter	Farmers-food for winter Food in fallout shelters Food for storms, tornadoes Saccharin products Scuba divers-air tank
	Water	Cactus, euphorbia, succulents Camel	Reservoirs Canteens Cooling ponds Cisterns
	Sun/Fossil Fuels	Phytoplankton-biomass for the night	Oil in salt domes Coal by utilities Wood piles for winter
Adjust to Use Less	Food/Nutrients	Bears-hibernation Birds-migration	Migrant workers
	Water	Ocotillo-dormant during dry season	Shower with a friend Brick in the toilet
	Heat	Deciduous trees-winter dormancy Fur, hair & seasonal insulation	Winter homes in the South
	Information		Live off storage-POW

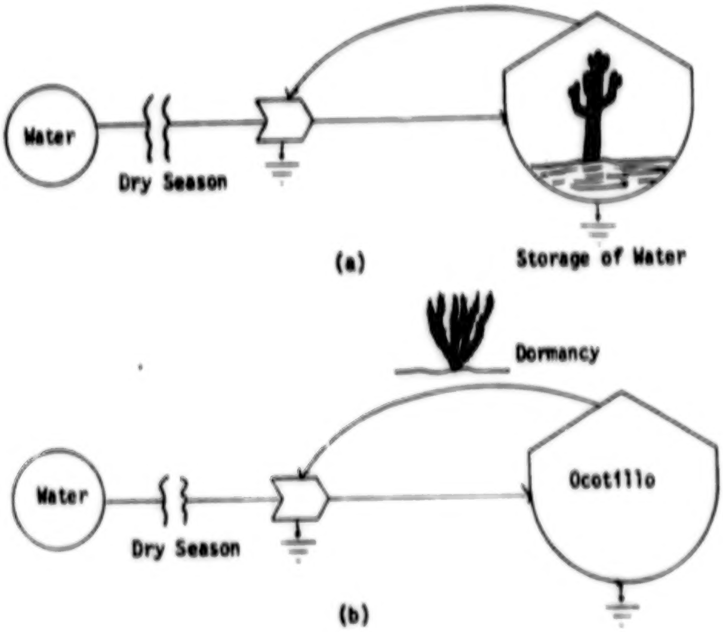


Fig. 11. System responses to an unreliable source in nonhuman systems: increase the storage size of the unreliable source (a) or adapt so as to use less (dormancy in b).

(Fig . 11a). By internalizing the source, temporary water limitations do not interfere with the normal functioning of the cactus.

Prior to periods when food or nutrients become unavailable, (such as northern winters), "stock-piling" is seen in nut storage by squirrels and honey storage by bees. These animals are able to live off their storages until the flow of food starts again in the spring. Similarly, plant seeds are a storage enabling the embryo to acquire nutrients until roots develop. Some ants (Myrmecocystus) store plant juices in workers so food will always be available regardless of the external source.

Sunlight is an irregular source, on during the day and off at night. As a result, phytoplankton must store (as biomass) at least enough solar energy to last through the night.

(2) Response: Adjust for less use.

Two commonly observed responses for not using a source where and when it is off are dormancy and migration.

Dormancy may be induced by temporary limitations of water, food, or heat supplies. As an alternative to storage of water for use in dry seasons, the Ocotillo (Fouquieria splendens) has adjusted to use water only when it is available. It grows and supports leaves only during the wet season, and becomes inactive, or dormant, when water is unavailable, or off (Figure 11b). Similarly, whereas squirrels create a food storage to carry them through the winter, bears have adjusted to minimal food requirements during this time. Through a decreased metabolic rate and activity, hibernation represents a way to limit the need for food. Deciduous trees, by winter leaf drop, go dormant as a means to survive winter weather when heat is unavailable.

Migration is also an alternative response to supply irregularities. Temporarily leaving an area which has become unable to supply necessary sources is seen in many migratory animal species. Shorebirds are known to follow the food "pulses" along the coast during Northern migrations.

B. Human Systems

As with nonhuman systems, supply irregularities cause human systems to increase storage size. Human systems also make temporary adaptations to not use the source when it is off.

(1) Response: Increase the storage size.

The U. S. is now responding to an unreliable source of oil by storing vast quantities of oil in salt domes. The Arab oil embargo of 1973 changed a reliable source into one perceived to be highly

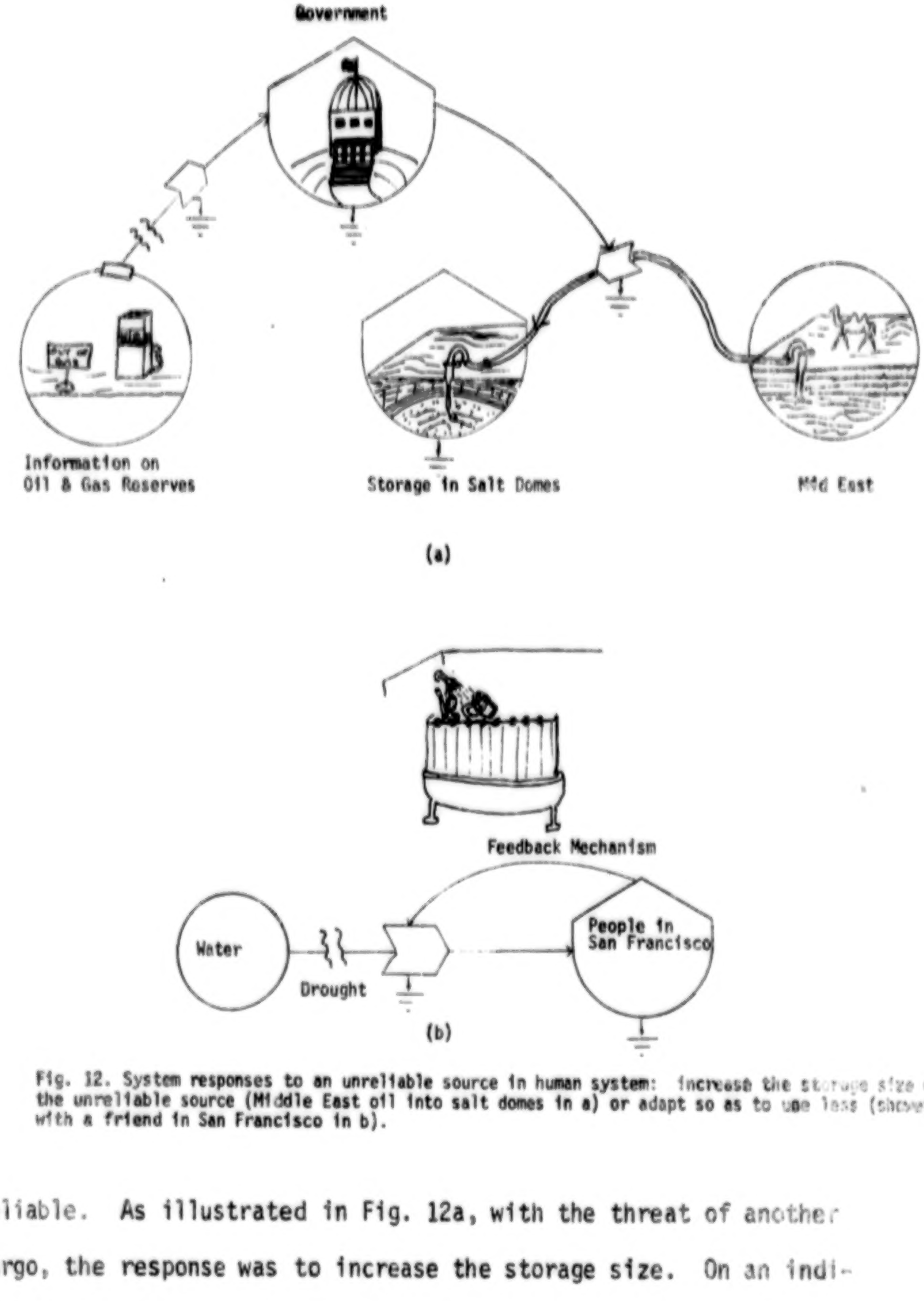


Fig. 12. System responses to an unreliable source in human system: increase the storage size of the unreliable source (Middle East oil into salt domes in a) or adapt so as to use less (showering with a friend in San Francisco in b).

unreliable. As illustrated in Fig. 12a, with the threat of another embargo, the response was to increase the storage size. On an individual basis, fuel was also stored privately as gas, oil, and wood. Similarly, electric utility companies store three to four month supplies of coal, a source perceived to be unreliable because of the threat of UMW strikes.

In order to use solar energy through technology it must be stored; the supply is "on" in the daytime, "off" at night and only partially "on" on cloudy days. The problems in storing solar energy are currently limiting the applications of solar technology. Other examples of storages as a response to supply irregularities include the stockpiling of saccharin products when threatened with a ban, money in a savings account, saved against a "rainy" day, and canning and freezing of vegetables and fruits for winter consumption.

(2) Response: Adjust for less use.

Many adaptations to use less of an unreliable source are observable in human systems. For example, during the recent drought in San Francisco, behavior modifications such as showering with a friend (Fig. 12b) or not showering at all were made in an effort to smooth out supply irregularities.

Migration is also observed in human systems as a way of "smoothing out" irregularities. Migrant workers, for example, leave an area when job potential disappears. This is temporary, however, as the following year, when crops are mature, the source of jobs is once again "on." Similarly, some people who live in northern climates, have second houses in the south. When the supply of heat is "off" during northern winters, they migrate southward.

Summary

An unreliable source is one which is periodically and temporarily limited. Systems respond by internalizing extra quantities of the source when it is "on" or by adjusting to not use it when it is "off." The responses of a system to a permanently limited source are somewhat different and are the subject of the next systems principle.

Limited Sources

Question: What is the response of a system to a limited source?

Principle: Systems respond by redesigning their mechanisms for using and acquiring the limited source or by obtaining a new source.

Discussion:

A limited source is one that, for the system, is always "off," as opposed to an unreliable one which is temporarily "off." The difference is only one of degree, and there is clearly a continuum from reliable and abundant (source always readily accessible) to unreliable (sometimes accessible) to limited (always in short supply). The continuum apparently operates within one system at any one time and among systems as they change with time.

The concept of limiting factors was first clearly expressed by Liebig in 1840 (7) as: "an organism is no stronger than the weakest link in its ecological chain" (8). An organism, an ecosystem, an industry, and a city must have essential materials just to sustain themselves. When the system is growing, the specific material that limits growth changes rapidly as the system responds to eliminate that limit, grows, and "faces" a different kind of limiting factor. In terms of Liebig's law of the minimum, only one factor, the one occurring at the critical minimum level, constrains further growth of the system.

Within any system, almost any source can be limited at a given time. For plants, sunlight, water, and nutrients may alternate as factors limiting the growth of the plant. Typically, plants respond to one kind of limiting factor by making some kind of adaptation, subsequently they grow by reinvesting their output until another factor becomes limiting. The process is one of continual response to whatever is limiting. All of the responses to competition, whether characteristics of animals in ecosystems or industries in a free market economy, can be viewed as responses and adaptations to continually changing limiting factors.

Succession of pioneer ecosystems to climax forests or towns to cities is characterized by continual responses to limiting factors through time. With the elimination of one limiting factor comes a period of growth and reinvestment, then the onset of another limiting factor, a new response, more growth, and so on. For ecosystems, the animal at the top of the food chain and the climax forest represent the steady state final form of this cycle of limit-response-growth. For human systems, most observers now believe there must be a steady state final form, but what form it will take and when it will come are highly uncertain. We might speculate that our big cities are at the top of the "food" chain and can grow no bigger, but they may change form as they respond to the host of limiting factors now besetting them.

We discuss three basic types of responses to limited supplies observed in both human and nonhuman systems: (i) protect the storage already established; (ii) develop complex mechanisms to obtain the limited source; (iii) develop a mechanism to obtain a new source. These responses, along with a few examples, will be discussed for nonhuman and human systems. Additional examples are given, by response type, in Table 5. There are undoubtedly hundreds more at all levels of complexity.

Table 5: Responses to Limited Sources: Examples in Nonhuman and Human Systems

Response	Examples	
	Nonhuman Systems	Human Systems
Protect the Storage[a]	Thorns, spines on desert plants (water) Altered photosynthetic process (water) Reptilian scales (water) Territorial behavior (food,water,mates) Recycle (nutrients) Natural herbicide production (nutrients) Large body volume to surface area (heat) Blubber, fur, hair (heat) Social behavior (mates)	Best Available Technology (clean water) Best Available Control Technology and Preventing Significant Deterioration (clean air) Coastal Zone Management Act (estuaries) National Parks (wilderness) War (land, political or religious beliefs) Recycle (glass, metal) Fence in land (privacy, food) Social behavior (mates, friends) Conservation movement (fossil fuels)
Develop a Mechanism to obtain the source[a]	Shallow, wide spreading root system of desert plants (surface water) Leaves to absorb water vapor (surface water) Symbiotic relationship (food) Agriculture (food) Parisitism (food, sunlight) Robbery (food, water) Large leaf area (sunlight) Use different wavelength (sunlight) Reptiles - large surface to volume ratio (heat) Tool use (food)	Water use (surface water) Pipelines (water, oil) Offshore oil (oil) World trade relations (various resources) Meditation (tranquility) Robbery, War (various resources) Agriculture (food)
Develop a Mechanism to obtain a new source[b]	Tap roots on plants (ground water) Air roots of epiphytes (water vapor) Leaves absorb water & nutrients from air (atmosphere, nutrients, water) Carnivorous plants (nutrients) Kangaroo rat (seed source for water) Nitrogen fixing bacteria (nutrients)	Cloud seeding (rain) Desalination, icebergs (clean surface water) Ocean exploration (various resources) Space exploration (?) Geothermal, solar, wind, oil shale (energy, Hybridization (food, ornamentals) Skyscrapers, subways (surface space) Fertilizer, vitamin pills, imitation meat (nutrients) Gasification, liquifaction (gas, oil) Coppertone (suntan) Synthetic material (cotton, silk, fur) Electricity (sunlight)

[a] The limited source is given in parentheses following the example.
[b] The new source is given in parentheses following the example.

A. Nonhuman Systems

(1) Response: Protect the storage already established.

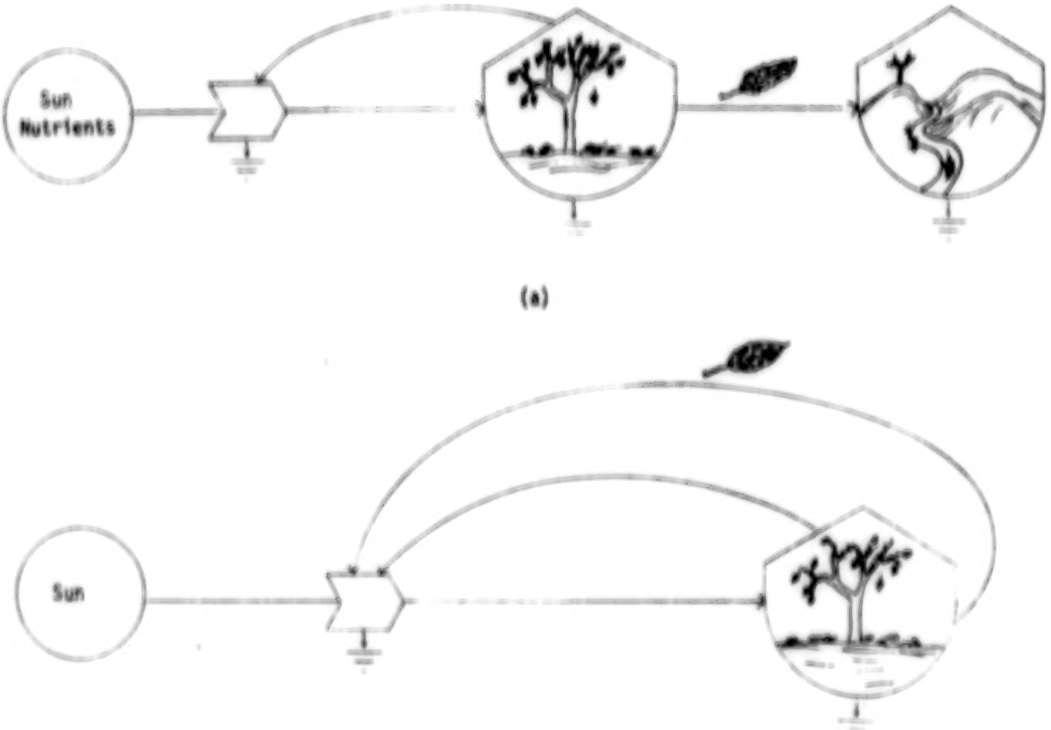
Protection involves the development of control mechanisms to "guard" the source and/or to use efficiently what is available.

Some desert plants have responded to surface water limitations by guarding their storage of water. The storage is the plant itself and structures such as thorns and spines are used to protect it from water seeking animals. Other desert plants, members of the Crassulaceae family, reduce water loss as a storage protection mechanism. They open their stomata only at night, to take in CO_2. The CO_2 is stored in an organic acid (crassulacic acid) which is used in photosynthesis the following day (when stomata are closed). The ability to keep stomata closed during the intense heat of a desert day greatly reduces water loss through evapotranspiration.

In northern climates where heat is limited, animals protect their internal heat storage. Characterized by a large body volume to surface area ratio; northern species minimize loss of heat through the skin surface. Fur, down, and blubber (as insulation) are also heat storage protection devices.

Territorial behavior in many animals is in response to the need to protect food resources because of intense competition and thus limits on supply. A well known example is that of the male wolf who "knows" through genetic information and socialization that keeping his territory posted and marked with urine assures access to food.

Systems may also respond to limited sources by recycling them. For example, when the nutrients in leaves are not recycled, nutrients



(a)

(b)

Fig. 13. A response to a limited source in nonhuman systems: protection of the nutrient storage through recycling. Loss to the system of nutrients in a nonlimiting situation (a) and recycled within the system in a limiting situation (b).

must be obtained externally (Fig. 13a). In contrast (Fig. 13b), recycling of leaves eliminates or greatly reduces the need for a nutrient source. Successional forests, characterized by open mineral cycles, acquire nutrients from external sources and allow those they do capture to escape. In contrast, as succession proceeds to climax, mineral cycles are closed and all nutrients acquired are held tightly in a recycling loop.

(2) Response: Develop complex mechanisms to obtain the limited source

As an alternative to protecting an existing storage, specialized, sometimes elaborate mechanisms such as symbiosis, parasitism, and robbery are designed to obtain the limited source. Some types of beetles produce imitation ant pheromones. By this mechanism, they gain access to ant nests and "steal" food. The weeping, or strangler fig (Ficus benjamina) relies on parisitism to obtain nutrients when it is young, because soil nutrients are limited for seedlings without developed root systems. The fig sprouts in the branch of a host and "feeds off" of it until the host is gone and the fig has a well developed root system for obtaining nutrients. The symbiotic relationship of legumes with nitrogen fixing bacteria allow the plant to obtain usable nitrogen and the bacteria an easily accessible food supply. Finally, fungus farming is a mechanism developed by some ants (Atta) to obtain limited food in the desert.

Responses to water limitations are similar. For example, the creosote bush (Larrea tridentata) in the desert establishes a specialized root system to acquire surface water. An areally extensive and shallow root structure enables the creosote bush to collect any surface water that is present.

Sunlight is a necessary input for photosynthesis and complex mechanisms for obtaining it occur under conditions where it is limited. For example, certain species of phytoplankton adapt to use only the wavelengths that remain at depths in lake and ocean water (where the full spectrum is limited). Similarly, the large leaves of understory plants in a rain forest represent a response to limited sunlight (Fig. 14a). As succession proceeds, the complexity and number of mechanisms which develop in response to continually changing limiting factors increases. Finally, with a climax system comes incredible diversity of specialization; "someone" has designed a mechanism to take advantage of every conceivable opportunity (niche) to obtain a resource. Everything external to the system is limiting its growth all of the time and it is in steady state.

(3) Response: Develop a mechanism for obtaining a new source.

Instead of, or in addition to, developing a mechanism for obtaining a limited source, the response may be to acquire a new source, replacing the old one. Examples of alternative sources to surface water and soil nutrients are given here.

Instead of establishing a mechanism to obtain surface water, mesquite (Prosopis juliflora) develops tap roots (extending 60 feet) to acquire ground water. Once this mechanism has been developed, surface water becomes unnecessary for mesquite and water no longer limits. Some trees, which grow where surface water is limited, have developed a mechanism to absorb nearly all the moisture they need from foggy and misty air. Frogs require standing surface water in which to lay their eggs. Natural standing water limitations in some areas have caused one species to find a new source; they lay their eggs in the water which accumulates in bromeliad cups. The desert dwelling kangaroo rat (Dipodomys merriami) manufactures water from plant seeds, breaking down the carbohydrates and recombining the acquired hydrogen with atmospheric oxygen.

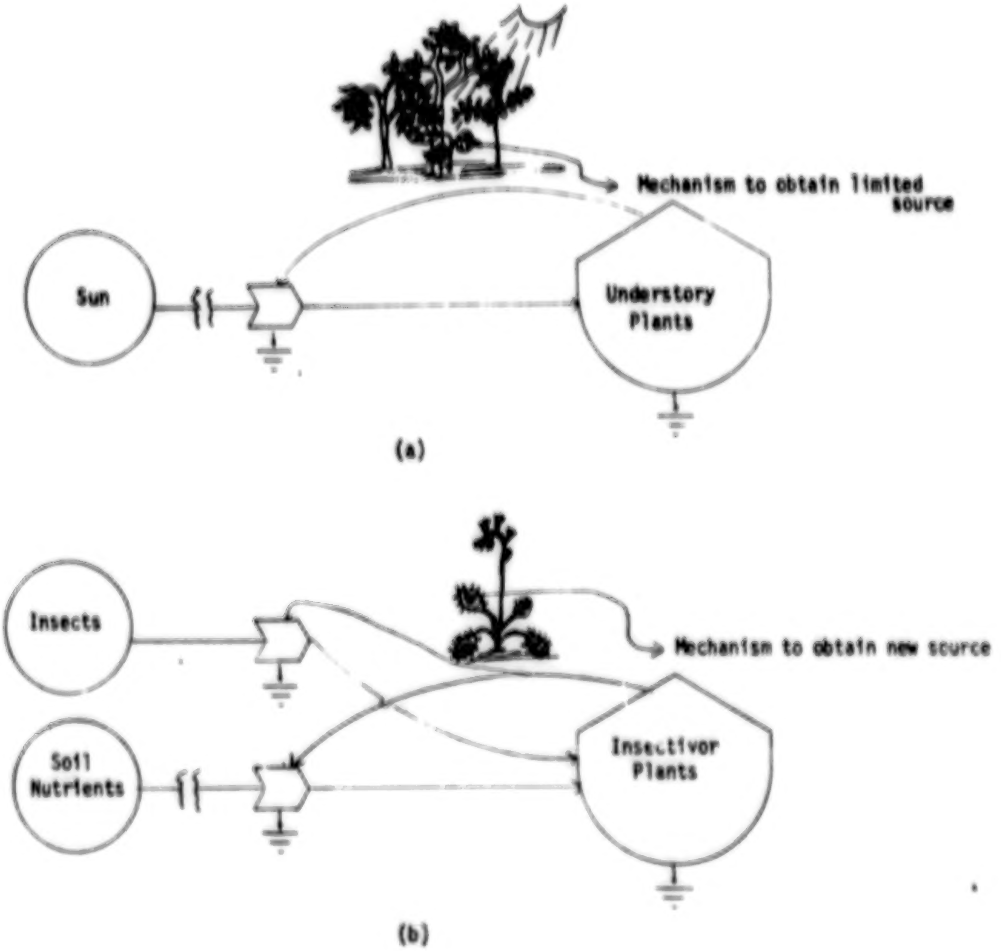

Mechanism to obtain limited source
Sun
Understory Plants
(a)
Insects
Mechanism to obtain new source
Soil Nutrients
Insectivor Plants
(b)

Fig. 14. Responses to a limited source in nonhuman systems: develop a new mechanism to acquire the limited source (a) or find a new source (b). Understory plants develop large leaves to acquire limited sunlight (a); a plant develops a new source of food (insects in b).

As an alternative to soil nutrients, some plants absorb them from the air (epiphytes). Still others, such as the sundew illustrated in Fig. 14b, have developed mechanisms to attract and "consume" insects. Note, in Fig. 14b, that the feedback from the storage is shown entering two "pumps," the old one which brings in soil nutrients and a new one which brings in insects. At the ecosystem level, new sources are acquired throughout succession until there are no more to acquire and, again, steady state sets in.

B. Human Systems

There are many examples of responses to supply limitations in human systems, but we are not sure if any of those responses or the combination of all of them represents the ultimate in the sense that a climax ecosystem does. Examples of the three response types are given but we can not carry the discussion through to a steady state type system.

(1) Response: Protect the storage already established.

In human systems, legal controls are commonly used to preserve or guard the storage of a limited source. For example, the concepts of Prevention of Significant Deterioration (PSD) and Best Available Control Technology (BACT) are mechanisms for preserving our now limited supply of clean air. They developed in response to a shortage.. Similarly, the concept of Best Available Technology in water quality control is a mechanism devised to preserve clean water which is now limited; and the Coastal Zone Management Act protects estuaries. National Parks and Wilderness Areas are a storage of wilderness and mechanisms for their protection are a result of supply limitations. The Endangered Species Act is designed to protect the U. S. storage of wildlife diversity.

As in nonhuman systems, recycling is another mechanism developed to protect and use efficiently what is already stored. As shown in Fig. 15a, fossil fuels are required to make bottles, and to dispose of them as waste. As fossil fuels become scarce, one mechanism proposed

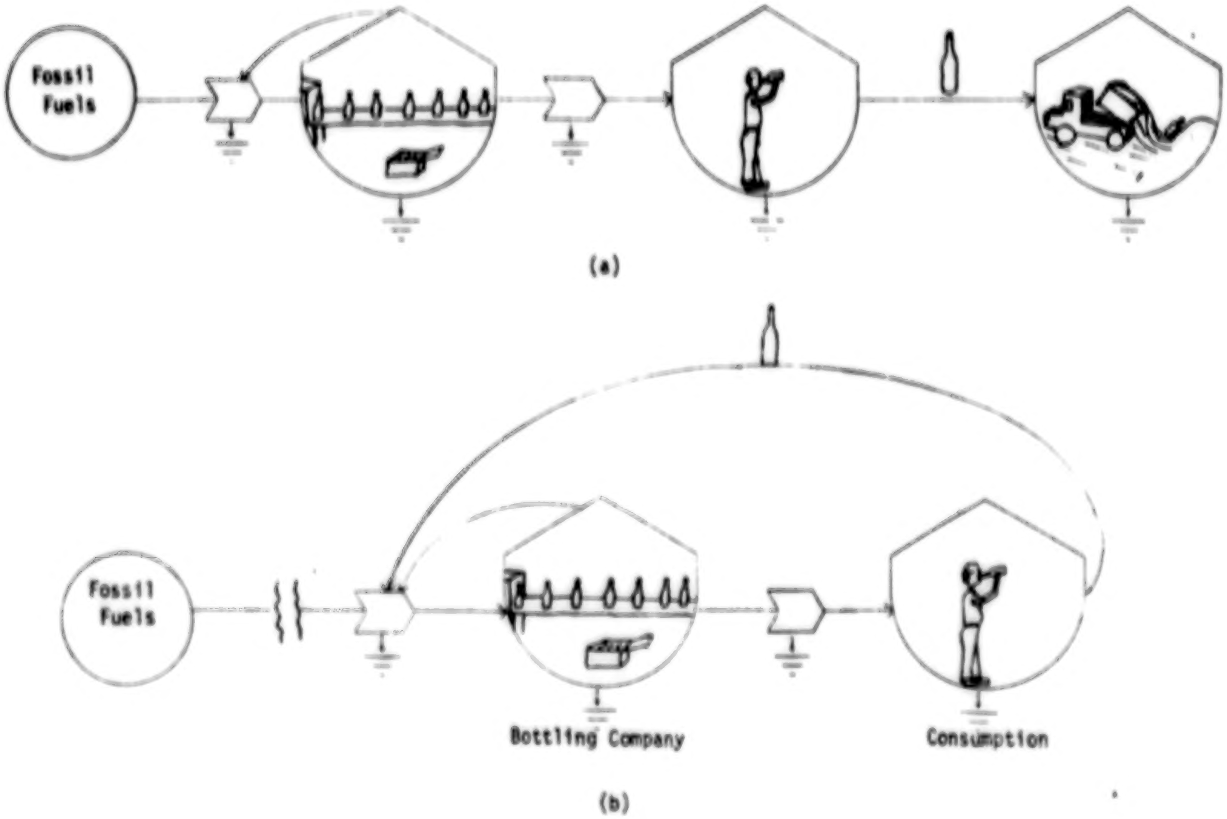


Fig. 15. A response to a limited source in human systems: protection of the oil storage through recycling. Loss to the system of the oil embodied in bottles in a nonlimiting situation (a) and bottle recycling within the system in a limiting situation (b).

to protect what we have is to recycle bottles (Fig. 15b). Recycling is an efficiency mechanism which decreases dependency on a limited external source.

(2) Response: Develop complex mechanisms to obtain the limited source.

A common mechanism used to obtain a source which is limited in one area is to import it from another area where it is not limited. As illustrated in Fig. 16a, oil is brought from Alaska for use in the contiguous states where it is limited. Similarly, when surface water is limited to one area, it may be piped in from somewhere else (Northern to Southern California). International trade represents a mechanism for obtaining a source limited in one country but not in another.

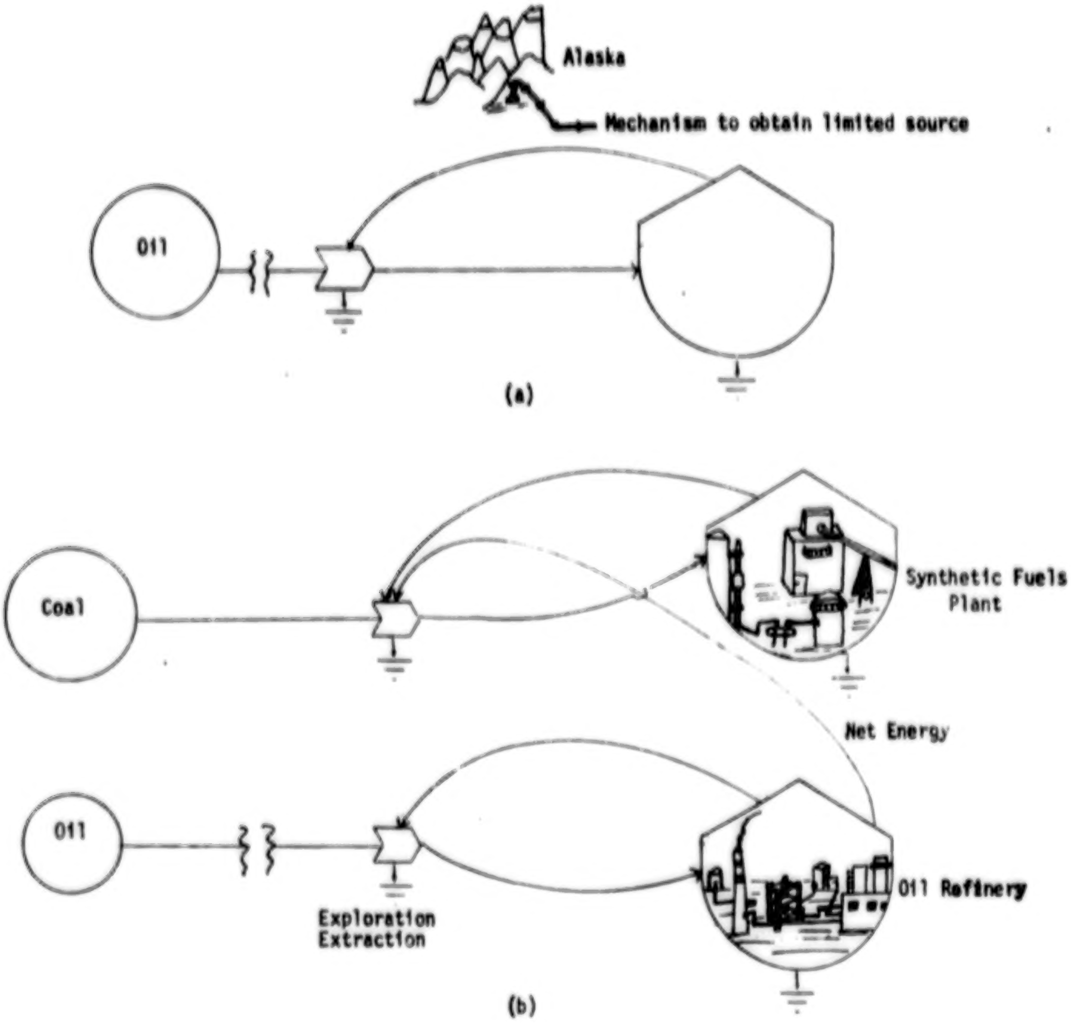


Fig. 16. Responses to a limited source in human systems: develop a new mechanism to acquire the limited source (a) or find a new source (b). Oil is imported from Alaska (a) or made from coal (b).

In human systems, war may develop in response to a limited source. For example, imperialistic wars are generally initiated to obtain natural resources and religious wars to obtain followers.

(3) Response: Develop a mechanism to obtain a new source.

Probably the most obvious case at the present time of finding a new source as the old one becomes limiting is manifested in the search for alternatives to crude oil and natural gas. Mechanisms for obtaining solar, geothermal and wind energy and for manufacturing oil and gas from coal and oil shale are being developed (Fig. 16b). Note in Fig. 16b, that the feedback investment from storage (the refinery) enters both the oil pump (bringing in crude oil) and the new pump (bringing in coal for synthetic oil). As the crude oil supply dwindles, the refinery storage disappears and the synthetic fuels storage grows. If one company owns both, the company is transformed from an oil company to a syn-fuels company.

Similarly, where fresh surface water is limited, rather than importing the same source, mechanisms for obtaining water from the air (cloud seeding) and from the ocean (desalination plants) develop. In the Middle East, where water is limited, a complex system for moving and melting icebergs is evolving. Space exploration offers a new way to obtain resources as well as political prestige. Fertilizer, vitamin pills and imitation meat represent nutrients made with oil instead of sunlight. Similarly, alcohol and drugs are used to "produce" relaxation and pleasure, both of which are in short supply for many people.

Summary

A system must make some adjustment to a limited source. Empirical evidence suggests that there are at least three common responses and hundreds of examples. If a supply of the source is already stored, protection of the storage through control mechanisms and efficient use is effective. Alternatively, the system may develop complex mechanisms to obtain the limited source or may develop mechanisms to acquire a new source. Factors that determine which specific response (out of a multitude of possible responses) occurs are the subject of the next systems principle.

Successful Responses

Question: From the myriad of responses and adaptations possible, what factors determine the specific response which develops and succeeds?

Principle: A response which is successful has the most favorable benefit/cost ratio.

Discussion:

Any response or adaptation has a cost associated with it. The system pays the price of responding by giving up part of what it has stored in order to establish the response mechanism. But once established, enormous benefits may accrue because of the new adaptation. Recall from Fig. 1a that the cost of the response is represented by the line labeled feedback cost (the expenditure required to "pump" in the source) and that the benefit of the response to the system is represented by the line labeled feedback effect. In the water and oil pump examples given earlier, the human pumping machine acquired more water than that perspired while pumping and the generator acquired more oil than that burned while pumping. The effect or benefit was greater than the cost. Odum (9) has hypothesized that the response mechanism which maximizes the effect/cost ratio is the mechanism which successfully develops in both nonhuman and human systems. He further suggests that a source is truly limited only when the cost of obtaining more of it exceeds the effect or the gains. For example, when the generator on the oil well is pumping out less oil than that needed to run the pump and maintain the generator, oil is truly limited. Steady state is thought to be a condition where cost equals effect. Much of Odum's and others' (10) recent research has been devoted to measuring that effect to cost ratio for all kinds of systems. The hypothesis is substantiated to the extent that measurements have been made.

Theories of natural selection suggest that species and ecosystems develop and test many kinds of responses until the "best" evolves and is sustained genetically. Human systems may very well operate under the same trial and error process, but may also have the ability to predict which of many alternative response designs is "best."

All of the examples of responses discussed above under the four principles are assumed to have developed successfully because they maximized (at least for some time period) the effect/cost ratio. Additional examples are discussed here in the context of this principle.

A. Nonhuman Systems

We have hypothesized that adaptations survive when they are energetically successful for the individual, species, or for a system with a more comprehensive boundary, such as an ecosystem or biome. On an individual level, camoflage coloration is an example of an energy cost (pigmentation, structural adaptations) for which the effect (protection or predatory advantage) is greater. Such a cost-effect is shown for a snake in Fig. 17a. Warning coloration and Mullerian and Batesian mimicry are examples of energy costs to individuals (death) with energy gains for the species (future

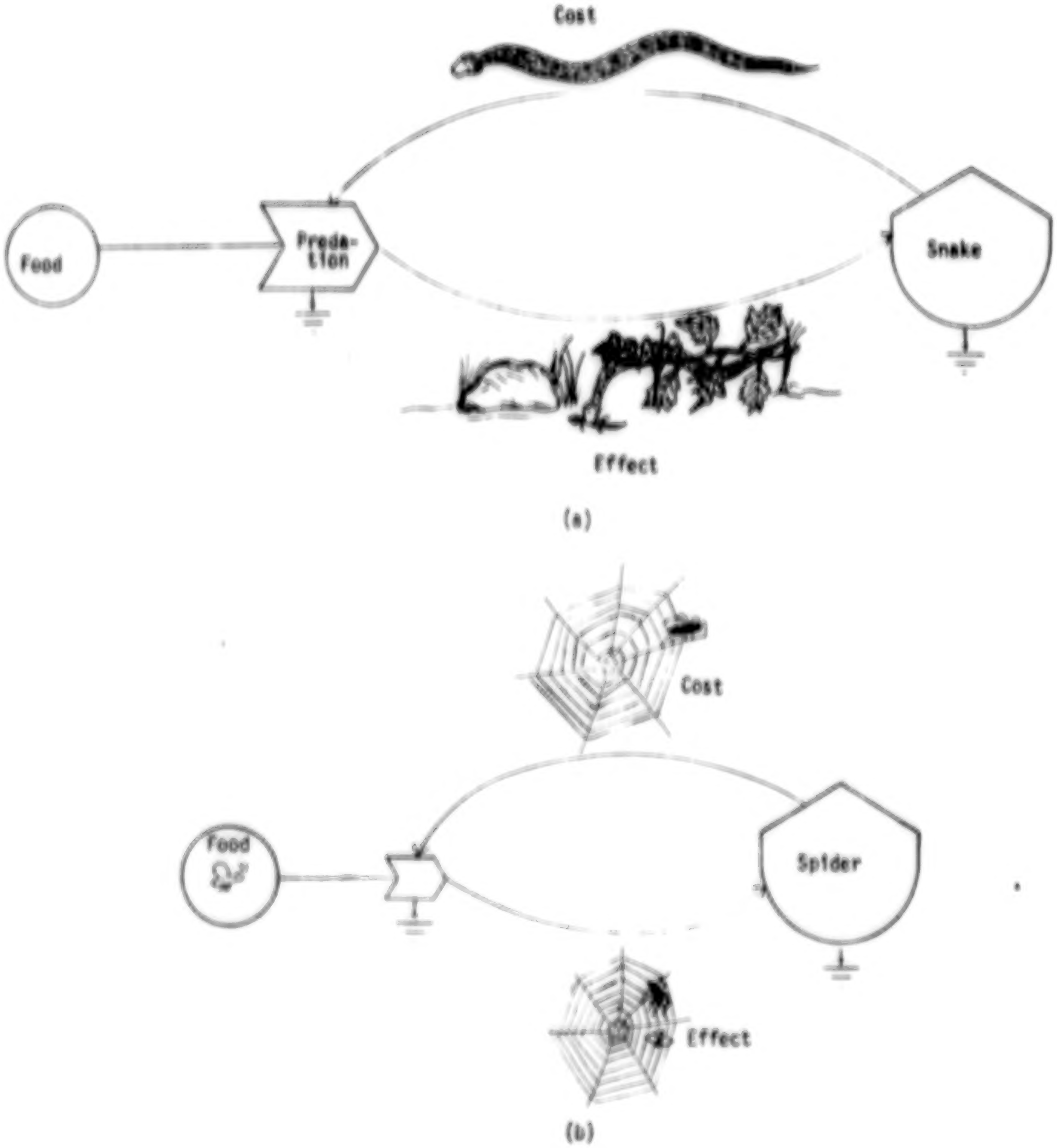


Fig. 17. Feedback cost and effect in nonhuman systems. Examples where costs are incurred for a greater effect include: pigmentation for a hunting advantage (a) and spinning webs for food acquisition (b).

protection). The energy intensive cicadan reproductive cycles, occurring only at prime number year intervals, decreases the probability that predators' life cycles will overlap and thus the energy gain is substantial. Similarly, the eight different kinds of silk produced by some spiders and their elaborate webs are energy costs with a great amplifying effect (Fig. 17b). Other examples include: various courtship displays and structures (such as the bower birds decorated nest; antlers on deer; mating plumage of birds; sex pheromones); the production of nectar by plants to insure pollination; the production and imitation by orchids of a female beetle pheromones and structures in order to attain cross pollination by the male beetle; and the acid in black walnut seeds which kills other encroaching plants.

At the ecosystem level, succession occurs at the expense (cost) of some species in one seral stage with the effect of greater production in the next seral stage. Diversity is attained at great cost, but the effect is stability through increased numbers of pathways for attaining and processing resources. At steady state in the climax ecosystem, the cost of establishing one more pathway or one more mechanism to attain and use the next unit of sunlight, water, or nutrients exceeds the effect in growth that attainment would have.

B. Human Systems

Many human/technological adaptations have not withstood the test of time so that we are less sure that they maximize benefits for minimum cost. To complicate matters, the human-technological system is clearly not in steady state and, thus, we should expect adaptations to be in a continual state of change. We hope and, in some cases consciously work toward, an ever increasing effect to cost ratio with new adaptations.

On an individual level costs are associated with physical exercise (e.g. jogging) with the effect of improved physical and mental health in the long and short term (Fig. 18a). The enormous quantity of resources spent on cosmetics and fashions are thought to assure a "better" mate and improved relations with other people. Investment in a college education has had clear benefits in occu-

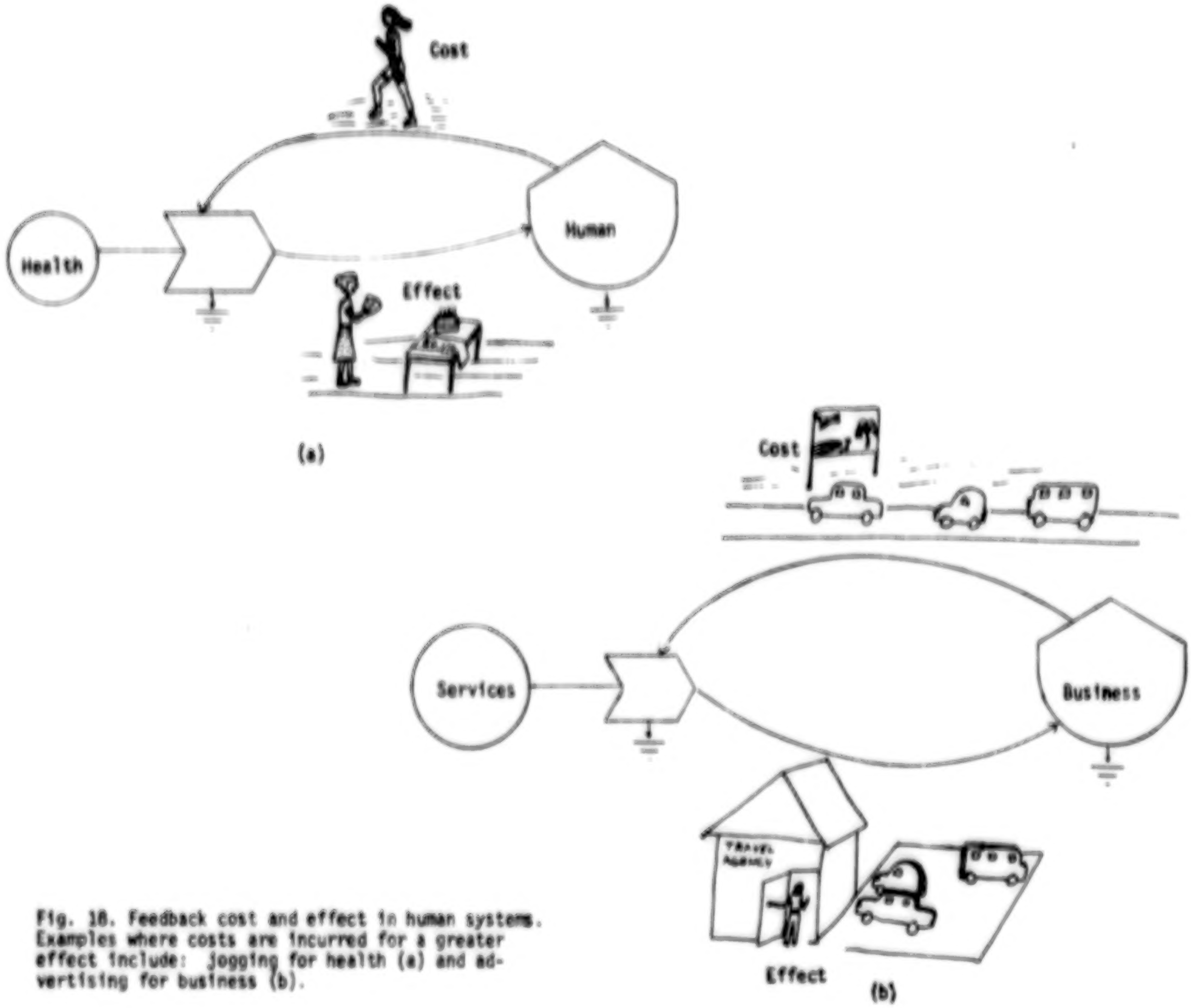


Fig. 18. Feedback cost and effect in human systems. Examples where costs are incurred for a greater effect include: jogging for health (a) and advertising for business (b).

pational success.

At the species level, certain cultural traits such as the upholding of morals and the "passing on" of traditions seem to give a society strength. In some societies, great costs are associated with adherence to certain religions, but the benefit of eternal life is perceived to be greater than those costs.

At the level of industries, advertising costs (Fig. 18b) have clear and measurable benefits to those who choose to incur them. The supply-demand balance that industries maintain is a manifestation of maximizing effect for minimum cost. In that case, price is effect; high demands cause high prices and vice versa. Industries choose demand responses based on a comparison of the marginal revenues they would receive for certain marginal costs they must pay.

In a city the Chamber of Commerce functions at a cost, but its promotional activities are thought to greatly benefit the city. City parks are established and maintained at a cost, but the quality of life benefits are thought to exceed those costs. As a whole, the diversity within cities comes at a cost but produces great benefits. Each person performs the highly specialized job function to which he or she is assigned and the entire city benefits. For example, people pay taxes so that government can pick up their garbage, provide their water, collect and treat their sewage, protect them from crime and fires, and educate their children. The people, in turn, now have time to perform some other task. For many women, the benefits in money which accrue from joining the labor force do not exceed the costs that are incurred in the form of child care and maid services. This poor benefit to cost situation keeps many women out of the labor force. Some join anyway working for less quantifiable benefits (e.g. personal growth) rather than for money.

At the level of federal bureaucracies, the corps of engineers regularly performs benefit/cost analyses of proposed water projects and is supposed to choose those with the highest benefit to cost ratio. Ratios which exceed one (benefit equal to cost) are mandatory. The U. S. Environmental Protection Agency continually tries to justify the costs of its regulatory programs by pointing to and even quantifying the health as well as other benefits. The welfare system in the U. S. is a cost for which effects are not clearly defined. Nuclear weapons, some political strategies, the practice of prolonging lifetimes through medicine and many other practices have not withstood "the test of time." For these we are not yet able to measure cost and effect and must rely on the same trial and error process of the nonhuman systems.

One area where we now believe that benefit/cost ratios can be measured and compared is that of alternative energy supply and consumption technologies. The concept of measuring and comparing the net energy ratios of alternative energy supply technologies is a process of measuring feedback effect and feedback cost. It is universally accepted that the net energy from domestic oil and gas wells have been declining. Some estimates indicate that oil in 1970 was produced with an effect to cost ratio of 45 to 1 while current production is between 6 and 15 to 1, depending on the source. Measuring effect to cost ratios has been institutionalized in Public Law 93-577 which mandates the U. S. Department of Energy to measure the net energy ratios of all non-nuclear technologies in the R+D stages.

Summary

It has been hypothesized, from empirical evidence, that the responses and adaptations which develop successfully are those which maximize an effect to cost ratio. For both nonhuman and human systems, various responses are tried; many fail and some succeed through some kind of natural selection at the systems level. Additionally, humans are learning how to measure and predict the effects and costs of alternative strategies and may be able to avoid the disadvantages of trial and error.

SUMMARY AND IMPLICATIONS

Fig. 19 diagrammatically represents a summary of the five principles. As it indicates, the principles, as a coherent whole, suggest that the "goal" of nonhuman and human systems is survival. Each principle describes how systems go about surviving under a variety of circumstances. Whatever the circumstance, survival seems to involve some mechanism for internalizing more of whatever sources are available externally. Sources are upgraded and stored in order to accelerate the influx of more resources which are converted to more net outputs (Principle I). Outputs are reinvested in order to further accelerate the influx of more resources (Principe II). Responses to irregular (Principle III) or limited (Principle IV) sources act to eliminate the irregularity or limit so that growth can continue. Responses which survive the test of time are those that pump in the most at the least cost (Principle V). Odum has summarized this apparent survival "ethic" in the "maximum power principle."

The implications of the five principles for urban planning and for National Park Service Planning are many. In urban planning, a major concern at the present time is the ever rising cost of maintaining cities and providing city services in the face of limited resources. Substantial agreement now exists that the basic limited resource is fossil fuel from domestic sources and that limits on its supply are a major cause of ever rising costs. Disagreement over just how major fossil fuel limits are and to what extent those limits cause inflation is substantial, but there is agreement that the "energy problem" is an important contributing factor to the inflationary spiral. Because

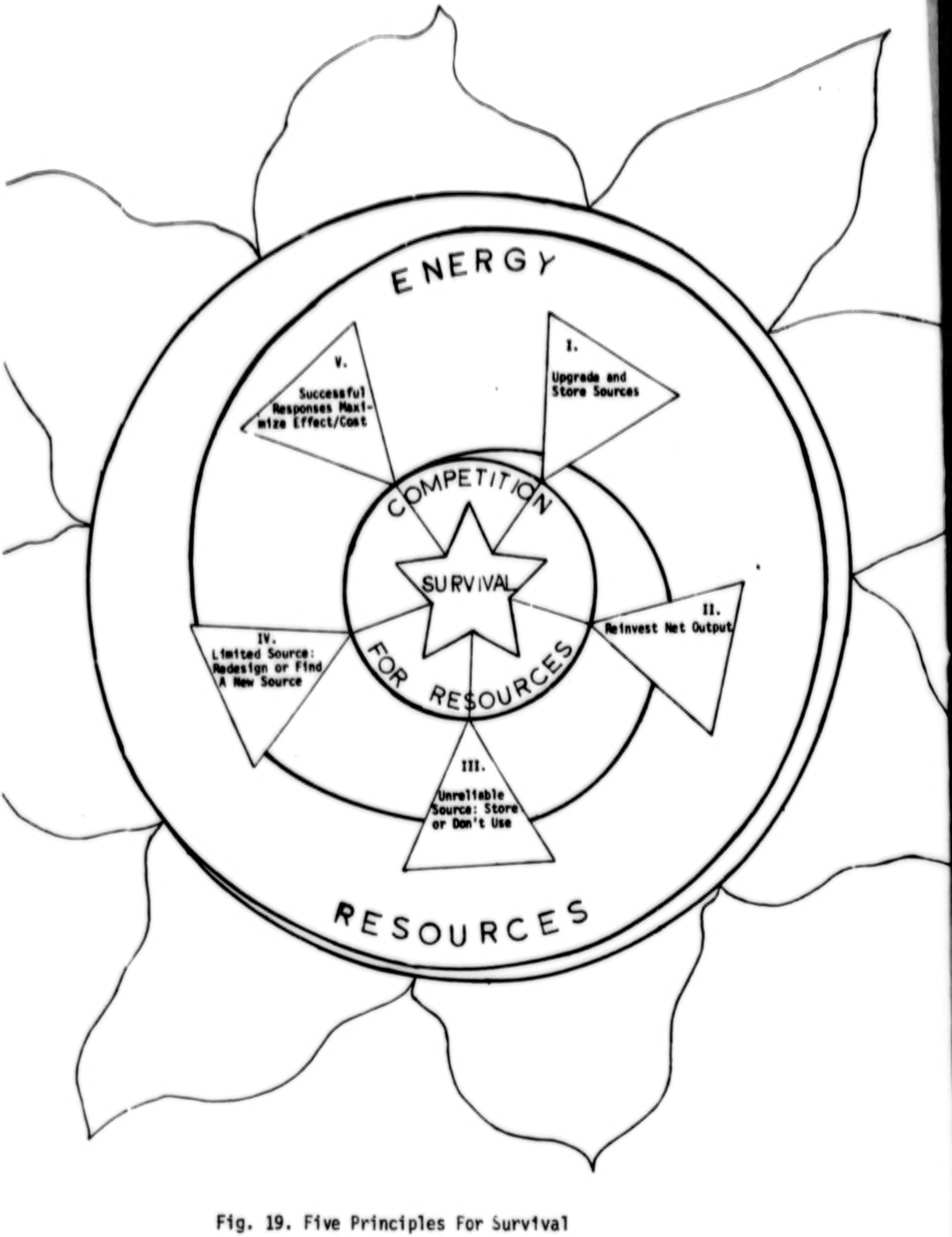

ENERGY
COMPETITION FOR RESOURCES
SURVIVAL
I. Upgrade and Store Sources
II. Reinvest Net Output
III. Unreliable Source: Store or Don't Use
IV. Limited Source: Redesign or Find A New Source
V. Successful Responses Maximize Effect/Cost
RESOURCES

Fig. 19. Five Principles For Survival

energy planning has become a high level issue within the Park Service and because the "energy problem" is at least partially responsible for present urban problems, we have chosen to discuss some implications of these principles for "solving the energy problem."

Both cities and National Parks contain nonhuman and human components, but cities are predominantly human systems and Parks are predominantly nonhuman systems. In either case, the combination is managed by people (city government or Park Service personnel). Whether fossil fuel is temporarily or permanently limited, both kinds of managers are planning responses to what are now limited supplies. Cities and National Parks, of course, do not literally have oil and gas reserves but they do consume oil and gas and they do use it and store it in many upgraded forms (as equipment, buildings, goods, and services, all manufactured with oil and gas). The limited supply systems principle (IV) suggests that planners ought to consider responses which protect the oil they have and responses which invoke new kinds of energy sources.*

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* The third response category given in Principle IV, that of identifying and developing new methods for acquiring oil is generally not a viable alternative for city government and Park managers. Both private industry and the U. S. Department of Energy are involved in such activities and there is little opportunity for direct participation of city government and Park managers. They can, of course, participate indirectly through their legislators. Because direct participation is not likely, this response category is excluded.

Protecting Existing Storages

The primary strategy adopted by nonhuman and human systems for protecting existing storages involves conservation. For Parks, conservation of fossil fuel can be brought about using many of the same strategies that have been proposed for the Nation; retrofit buildings with insulation, recycle cans and bottles, establish and apply efficiency standards for all purchased appliances, institute automatic thermostat control systems for night thermostat setback, reduce water consumption, manage electric demand for reduction of peak loads, reduce overall lighting and concentrate "task lighting."

Additional opportunities in the transportation sector include: the use of high mileage vehicles, reduction in vehicle miles traveled through increased occupancy or through a reduction in the number and distance of trips, and a shift in passenger movement to more energy efficient modes of travel. More specifically, a reduction in vehicle miles traveled can be accomplished by "park and ride" lots or by expanding the Park System in urban areas. A shift in modes of travel might include visitor access to mopeds and bicycles upon arrival to the Park. Expansion of the road system might be limited and alternatives such as bikeways expanded.

Acquiring New Sources

Probably the most exciting potential responses to limited oil supplies are those which involve new sources of energy. In particular, responses which couple the nonhuman and human components of Parks and Cities offer substantial opportunities for reduction in fossil fuel consumption. The nonhuman components are already running on solar power; coupling that solar power to the human components represents a direct substitution of solar energy for oil. Natural ecosystems are already constructed and are highly evolved. They are capable of providing goods and services needed by the human components and of assimilating and diluting degradable wastes.

In particular, extant environmental resources running on solar power can be substituted for oil in buildings, for waste management, and in landscape planning. In buildings, passive solar heating systems where temperature is controlled partially by vegetation and "the ground" represent a replacement of oil with solar energy for space conditioning. For residential buildings, the oil savings can be 20 to 30% (11). Other examples of substitution of solar power for oil in buildings include the use of heat pumps (which use solar induced heat gradients for space heating and cooling), of attic fans (which rely on natural wind for ventilation), and of natural (solar) lighting.

Natural environments can also function as energy efficient and inexpensive waste management systems. When the by-products of the human subsystem are coupled to the nonhuman subsystem, the oil used to treat and dispose of those by-products is replaced with solar energy. For example, the use of treated sewage effluent for irrigation of lawn areas in Parks or of Parks in cities is coming into widespread use. Combinations of sewage sludge and organic refuse can replace fertilizers made with natural gas. In Parks, the use of wastepaper as an energy source has been suggested.

Finally, for cities, it has been shown (12) that Parks contribute directly to reductions both in fossil fuel use and in city budgets. Urban forests run on solar power and urban technologies run on fossil fuel. The challenge is to interface the two in a symbiotic relationship that enchances the contribution of both to the city's vitality. Fig. 20a summarizes the present urban situation running almost entirely on fossil fuel. Fossil fuel is consumed to manufacture goods and services within the city and to dispose of wastes from technology and from people. In contrast, Fig. 20b illustrates a symbiotic relationship between nonhuman and human components; note that feedbacks from existing storages act to bring solar power to the city through the establishment of urban forests and parks. The urban forests and parks, then, contribute some of the goods and services to people that were provided by fossil fuel based technologies. Using solar energy, the forest can provide noise control, erosion control, aquifer recharge, space heating and cooling for buildings, wastewater treatment, air quality control, and recreation. Stanford (13) has outlined such a strategy in great detail for large cities. The point is that a coupling of solar powered nonhuman systems to fossil fuel powered technological systems offers the potential to save fossil fuel, to mitigate the exponential rise in the cost of maintaining cities, and to bring Parks to the people.

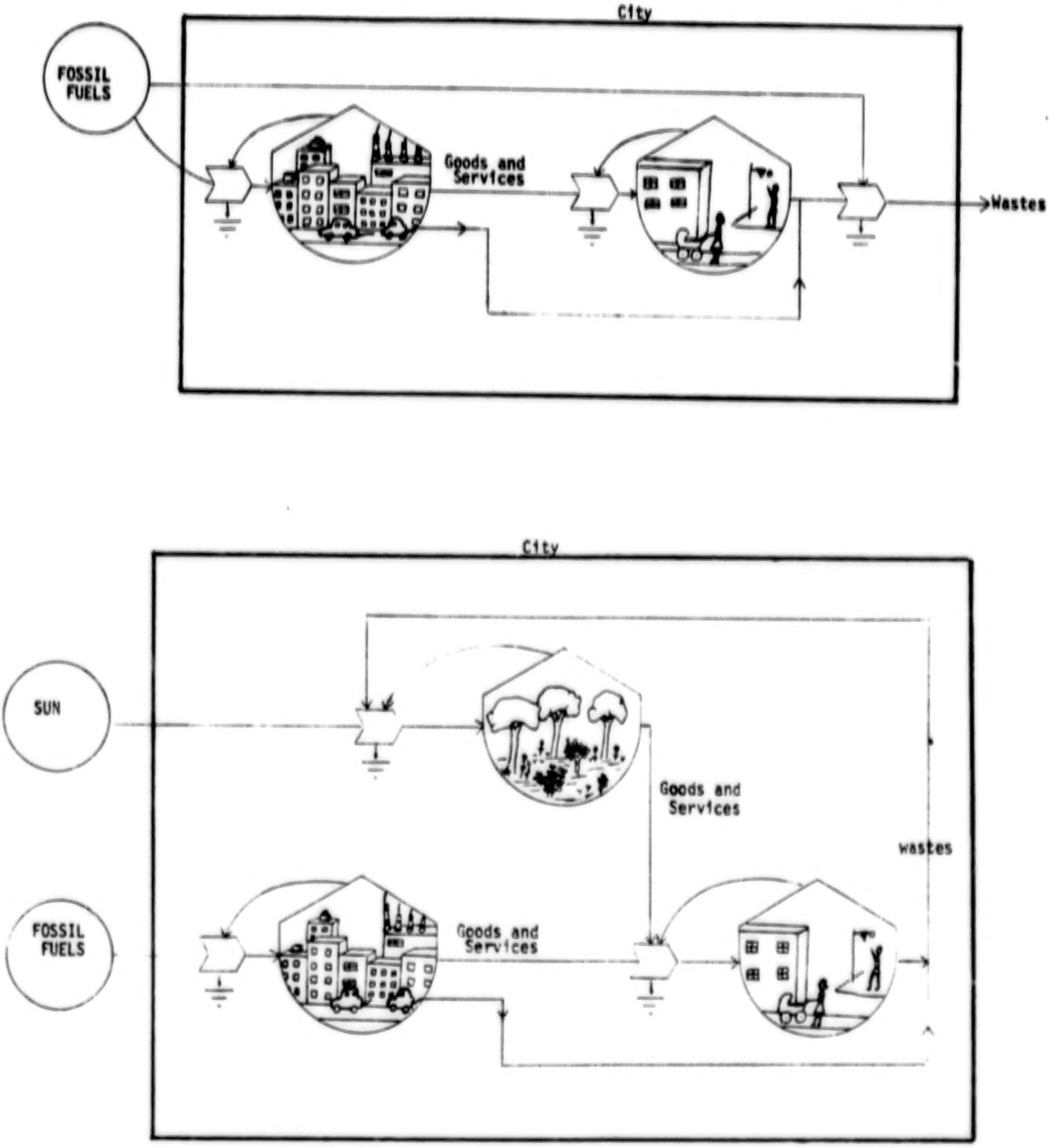

Fig. 20. A fossil fuel based city (a) and a solar and fossil fuel based city (b). Outputs from existing storages (a) are used to internalize solar power via urban forests (b).

The Challenge

Choosing among the variety of response strategies to limited oil and gas supplies will require at least two kinds of information. First, the quantity of fossil fuel used and the way it is used must be identified. That is, an energy audit is required to identify where in the Park system significant quantities of fossil fuel are utilized. Secondly, the costs and benefits (effects) of each of a set of alternative strategies for implementing a change ought to be measured. Costs and effects for many of the strategies suggested here have been measured for certain applications. For example, one study (14) showed that for each one Btu of energy invested in insulation (a cost), four Btu's are saved (an effect). However, for many of the more exotic new sources of energy such as active solar collectors, photovoltaics, and geothermal, cost and effect have not been measured. Additionally, information is just now accumulating on the specific needs of Parks and on the quantities of by-products that are produced in them by the human subsystems. The challenge is to acquire energy use information, to identify appropriate response strategies, to choose among them by considering their cost and effect, and to manage their implementation.

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